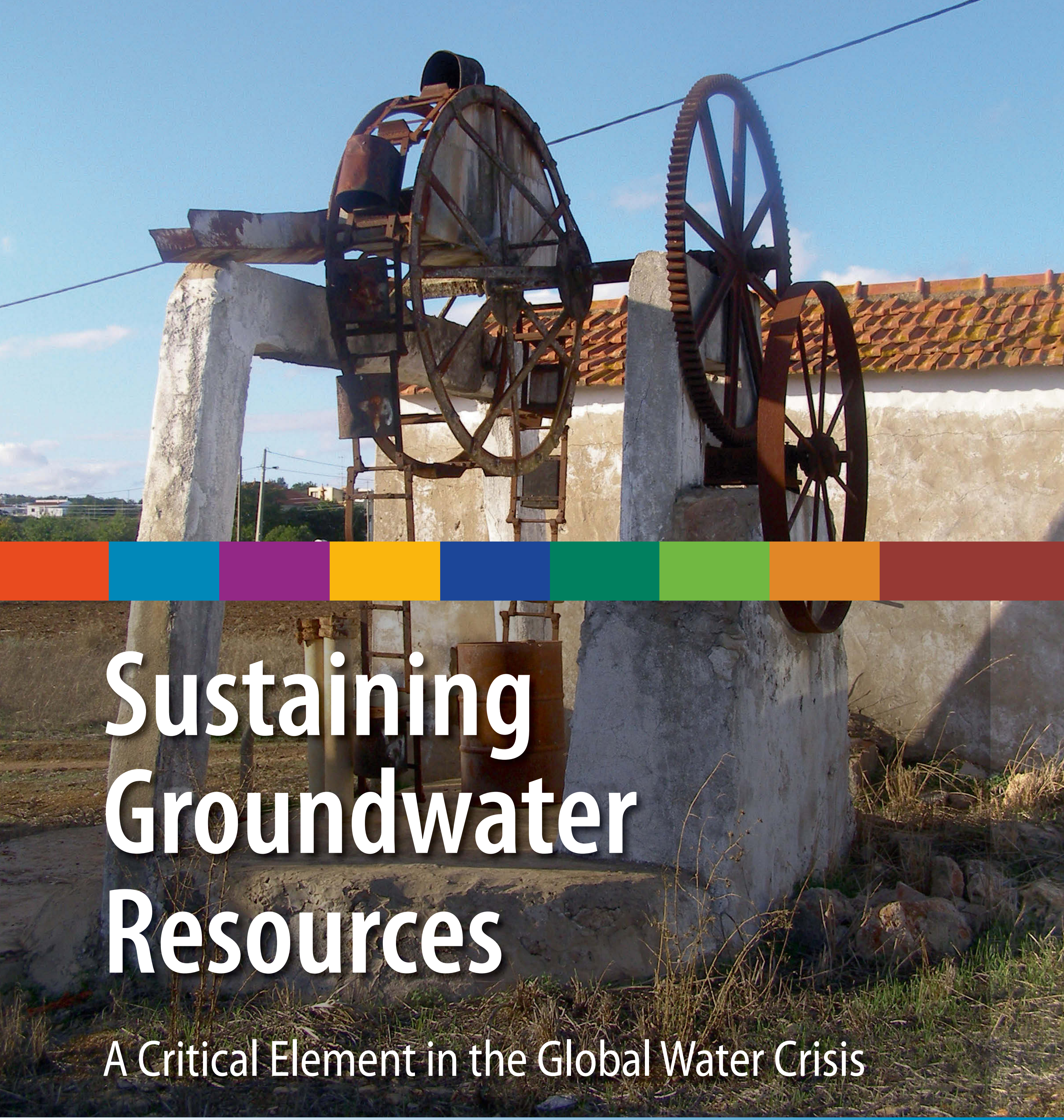

# Sustaining Groundwater Resources

## A Critical Element in the Global Water Crisis

International Geographical Union
Commission for Water Sustainability

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Earth Sciences for Society

J. A. A. Jones (Ed.)

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# Sustaining Groundwater Resources

# International Year of Planet Earth

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**Series Editors:**

Eduardo F.J. de Mulder
Executive Director International Secretariat
International Year of Planet Earth

Edward Derbyshire
Goodwill Ambassador
International Year of Planet Earth

The book series is dedicated to the United Nations International Year of Planet Earth. The aim of the Year is to raise worldwide public and political awareness of the vast (but often under-used) potential of Earth sciences for improving the quality of life and safeguarding the planet. Geoscientific knowledge can save lives and protect property if threatened by natural disasters. Such knowledge is also needed to sustainably satisfy the growing need for Earth's resources by more people. Earth scientists are ready to contribute to a safer, healthier and more prosperous society. IYPE aims to develop a new generation of such experts to find new resources and to develop land more sustainably.

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J. Anthony A. Jones
Editor

# Sustaining Groundwater Resources

## A Critical Element in the Global Water Crisis

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International
Geographical Union
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Water Sustainability

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# Foreword

The International Year of Planet Earth (IYPE) was established as a means of raising worldwide public and political awareness of the vast, though frequently under-used, potential the earth sciences possess for improving the quality of life of the peoples of the world and safeguarding Earth's rich and diverse environments.

The International Year project was jointly initiated in 2000 by the International Union of Geological Sciences (IUGS) and the Earth Science Division of the United Nations Educational, Scientific and Cultural Organisation (UNESCO). IUGS, which is a non-governmental organization, and UNESCO, an inter-governmental organization, already shared a long record of productive cooperation in the natural sciences and their application to societal problems, including the International Geoscience Programme (IGCP) now in its fourth decade.

With its main goals of raising public awareness of and enhancing research in the Earth sciences on a global scale in both the developed and less-developed countries of the world, two operational programmes were demanded. In 2002 and 2003, the series editors together with Dr. Ted Nield and Dr. Henk Schalke (all four being core members of the Management Team at that time) drew up outlines of a science and an outreach programme. In 2005, following the UN proclamation of 2008 as the United Nations International Year of Planet Earth, the "year" grew into a triennium (2007–2009).

The outreach programme, targeting all levels of human society from decision makers to the general public, achieved considerable success in the hands of member states representing over 80% of the global population. The science programme concentrated on bringing together like-minded scientists from around the world to advance collaborative science in a number of areas of global concern. A strong emphasis on enhancing the role of the Earth sciences in building a healthier, safer and wealthier society was adopted – as declared in the Year's logo strap-line "Earth Sciences *for* Society".

The organizational approach adopted by the science programme involved recognition of 10 global themes that embrace a broad range of problems of widespread national and international concern, as follows:

- Human health: this theme involves improving understanding of the processes by which geological materials affect human health as a means identifying and reducing a range of pathological effects.
- Climate: particularly emphasizes improved detail and understanding of the non-human factor in climate change.
- Groundwater: considers the occurrence, quantity and quality of this vital resource for all living things against a background that includes potential political tension between competing neighbour nations.

- Ocean: aims to improve understanding of the processes and environment of the ocean floors with relevance to the history of planet Earth and the potential for improved understanding of life and resources.
- Soils: this thin "skin" on Earth's surface is the vital source of nutrients that sustain life on the world's landmasses, but this living skin is vulnerable to degradation if not used wisely. This theme emphasizes greater use of soil science information in the selection, use and ensuring sustainability of agricultural soils so as to enhance production and diminish soil loss.
- Deep Earth: in view of the fundamental importance of deep the Earth in supplying basic needs, including mitigating the impact of certain natural hazards and controlling environmental degradation, this theme concentrates on developing scientific models that assist in the reconstruction of past processes and the forecasting of future processes that take place in the solid Earth.
- Megacities: this theme is concerned with means of building safer structures and expanding urban areas, including utilization of subsurface space.
- Geohazards: aims to reduce the risks posed to human communities by both natural and human-induced hazards using current knowledge and new information derived from research.
- Resources: involves advancing our knowledge of Earth's natural resources and their sustainable extraction.
- Earth and Life: it is over 2½ billion years since the first effects of life began to affect Earth's atmosphere, oceans and landmasses. Earth's biological "cloak", known as the biosphere, makes our planet unique but it needs to be better known and protected. This theme aims to advance understanding of the dynamic processes of the biosphere and to use that understanding to help keep this global life-support system in good health for the benefit of all living things.

The first task of the leading Earth scientists appointed as theme leaders was the production of a set of theme brochures. Some 3500 of these were published, initially in English only but later translated into Portuguese, Chinese, Hungarian, Vietnamese, Italian, Spanish, Turkish, Lithuanian, Polish, Arabic, Japanese and Greek. Most of these were published in hard copy and all are listed on the IYPE web site.

It is fitting that, as the International Year's triennium terminates at the end of 2009, the more than 100 scientists who participated in the 10 science themes should bring together the results of their wide ranging international deliberations in a series of state-of-the-art volumes that will stand as a legacy of the International Year of Planet Earth. The book series was a direct result of interaction between the International Year and the Springer Verlag Company, a partnership which was formalized in 2008 during the acme of the triennium.

This IYPE-Springer book series contains the latest thinking on the chosen themes by a large number of earth science professionals from around the world. The books are written at the advanced level demanded by a potential readership consisting of Earth science professionals and students. Thus, the series is a legacy of the science programme, but it is also a counterweight to the earth science information in several media formats already delivered by the numerous national committees of the International Year in their pursuit of worldwide popularization under the outreach programme.

The discerning reader will recognize that the books in this series provide not only a comprehensive account of the individual themes but also share much common ground that makes the series greater than the sum of the individual volumes. It is to be hoped that the scientific perspective thus provided will enhance the reader's appreciation of the nature and scale of earth science as well as the guidance it can offer to governments, decision makers and others seeking solutions to national and global problems, thereby improving everyday life for present and future residents of planet Earth.

Eduardo F.J. de Mulder
Executive Director International Secretariat
International Year of Planet Earth

Edward Derbyshire
Goodwill Ambassador
International Year of Planet Earth

# Series Preface

This book series is one of the many important results of the International Year of Planet Earth (IYPE), a joint initiative of UNESCO and the International Union of Geological Sciences (IUGS), launched with the aim of ensuring greater and more effective use by society of the knowledge and skills provided by the earth sciences.

It was originally intended that the IYPE would run from the beginning of 2007 until the end of 2009, with the core year of the triennium (2008) being proclaimed as a UN Year by the United Nations General Assembly. During all 3 years, a series of activities included in the IYPE's science and outreach programmes had a strong mobilizing effect around the globe, not only among earth scientists but also within the general public and, especially, among children and young people.

The outreach programme has served to enhance cooperation among earth scientists, administrators, politicians and civil society and to generate public awareness of the wide ranging importance of the geosciences for human life and prosperity. It has also helped to develop a better understanding of Planet Earth and the importance of this knowledge in building of a safer, healthier, and wealthier society.

The scientific programme, focused upon 10 themes of relevance to society, has successfully raised geoscientists' awareness of the need to develop further the international coordination of their activities. The programme has also led to some important updating of the main challenges the geosciences are, and will be confronting within an agenda closely focused on societal benefit.

An important outcome of the work of the IYPE's scientific themes includes this thematic book as one of the volumes making up the IYPE-Springer Series, which was designed to provide an important element of the legacy of the International Year of Planet Earth. Many prestigious scientists, drawn from different disciplines and with a wide range of nationalities, are warmly thanked for their contributions to a series of books that epitomize the most advanced, up-to-date and useful information on evolution and life, water resources, soils, changing climate, deep earth, oceans, non-renewable resources, earth and health, natural hazards, and megacities.

This legacy opens a bridge to the future. It is published in the hope that the core message and the concerted actions of the International Year of Planet Earth throughout the triennium will continue and, ultimately, go some way toward helping to establish an improved equilibrium between human society and its home planet. As stated by the Director General of UNESCO, Koichiro Matsuura, "Our knowledge of the Earth system is our insurance policy for the future of our planet". This book series is an important step in that direction.

R. Missotten
Chief, Global Earth Observation Section
UNESCO

ARiccardi
Alberto C. Riccardi
President
IUGS

# Preface

This volume commemorates the International Year of Planet Earth. The UN General Assembly ratified the IYPE in 2005 and the International Year was launched with great ceremony at the UNESCO HQ in Paris in February 2008. The International Union of Geological Sciences (IUGS) and the International Geographical Union (IGU) were among the prime initiators. This book is a contribution from the IYPE Groundwater team and from the IGU Commission for Water Sustainability.

The IYPE celebrates 50 years since the International Geophysical Year kick-started global collaboration in the geosciences in 1957–1958. In the 1950s, the only water-related activities in the IGY were in glaciology and the emphasis was purely on the physical science. The world has changed very much since then. In many ways it seems more hazardous, and science is focusing more and more on service to humanity. The themes of the IYPE include megacities, climate change, soils, natural resources, hazards, and health and life, as well as deep geology and the ocean, and, of course, groundwater, the topic of this volume.

In preparation for the IYPE, the International Council for Science (ICSU) established the Geo-Unions Joint Science Programme in 2004. As part of this programme, the ICSU Groundwater Committee, under the chairmanship of Dr. Mary Hill (USGS), produced the brochure *Groundwater – reservoir for a thirsty planet*, which was published by the IUGS in 2005. The brochure outlined the key issues facing groundwater resources in the 21st century: rising rates of abstract and over-exploitation, pollution, lack of agreement over internationally shared aquifers, and undervaluing groundwater as a vital resource for both human beings and the environment.

Each theme within the IYPE has been administered by a “science implementation team” (SIT) that vetted proposals for a key research project to be selected as a flagship for the IYPE. The Groundwater SIT selected a project put forward by Dr. Steve Silliman of Notre Dame University, Notre Dame, IN, USA, in collaboration with colleagues from Bénin. The IYPE’s “badging” of this project allowed the group to acquire sufficient resources to continue work for another 4 years. The ongoing research, which is reported later in this volume, is identifying the threats to groundwater in Benin, especially the spread of saltwater intrusion in coastal aquifers, and testing new solutions. It involves a combination of modelling, field research, and interaction with the local population. Getting local government to maintain a network of observation wells is a major aim.

The SIT held its defining conference at the 33rd International Geological Congress organised by the IUGS in Oslo 2008, at which most of the contributors to this Legacy volume delivered research papers. The team also sponsored two other international conferences on groundwater: the International Conference on Groundwater Dynamics and Global Change, organised by Professor Amarendra Sinha at the

University of Rajasthan in Jaipur, which was co-sponsored by the International Hydrological Programme, UNICEF, and the Indian Department for Science and Technology, and the Workshop on Aquifer Storage and Recovery Methods organised by the Deputy Leader of the SIT, Professor J.P. Lobo Ferreira, Head of the Groundwater Section at the Portuguese National Laboratory for Civil Engineering (LNEC) in Lisbon.

As the world population burgeons, human demand for water expands and one in ten rivers run dry for part of the year; humankind is turning increasingly to groundwater as a resource. Like oil reserves, the true extent of groundwater reserves is difficult to estimate and, whilst billions of dollars have been spent searching for valuable oil reserves, groundwater has rarely been ascribed a monetary value at all. As a result, most exploitation has been based on relatively unsophisticated exploratory methods, estimates of available reserves have been and continue to be largely based on limited data, and the world is only just waking up to the long-term damage done by reckless pollution. This comes right at the time that many parts of the world are turning more and more to groundwater as a supposedly reliable source of water and when impending climate change is set to have significant impacts on resources in many regions, especially in areas already under stress.

This volume aims to highlight these issues and to try to point towards ways of overcoming the problems.

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# Groundwater in Peril

J. Anthony A. Jones

**Abstract**

Groundwater is being exploited, overexploited and polluted as never before. Agriculture is a major cause, with rising levels of irrigation and overuse of artificial fertilisers. High levels of pollution in surface water bodies have also led to greater use of groundwater. In some areas, however, downdraft has led to oxidation of bedrocks and release of arsenic, most notably in West Bengal and Bangladesh. Falling water tables in the Ganges delta may be intensified by management of surface water, especially river diversions. Internationally shared aquifers, as between Israel and the West Bank, continue to be a source of disagreement and present a potential cause for 'water wars', although the 'Berlin Rules' brought groundwater into the realm of international law for the first time in 2004. Less well publicised is the complex interaction between groundwater and the sea, with groundwater acting as both victim and booster. The latest drive to extract oil and gas from shales by 'hydrofracking' holds new threats for groundwater resources. So too does climate change. Sustainable management of groundwater resources will require better monitoring; data capture; storage and accessibility; improved modelling; more efficient water use, particularly in agriculture; and more measures to improve groundwater recharge.

**Keywords**

Groundwater • Pollution • Overdraft • Salinisation • Sea level rise • Shale oil • Arsenic • Uranium • Artificial recharge • Internationally shared aquifers

## Introduction

Groundwater is a vital resource for many people around the world. As surface water supplies are diminishing or becoming polluted, people are turning increasingly to groundwater. Yet groundwater reserves are also suffering, as a result of overexploitation, pollution and climate change. Whilst the impact of climate change on glaciers and ice sheets is receiving wide media attention, the future of groundwater resources hardly gets a mention. For most human societies, what is happening to groundwater resources is at least as important, if not more so. Loss of ice resources is a serious concern for communities that depend on meltwaters from the Himalayas, Andes,

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Alps and Rockies, but groundwater resources are far more widespread, closer to the majority of the world population, more heavily exploited and more vulnerable to pollution from agriculture, industry and human wastewaters.

Nearly half of the world population get their drinking water from groundwater. According to the World Water Assessment Programme (2009), groundwater provides over 18% of all water withdrawals and 48% of drinking water. In many regions most drinking water comes from groundwater. It accounts for over 70% of public water supplies in Germany; nearer 80% in Russia; and for almost 100% in Austria, Denmark and Lithuania. The same is true in North Africa and the Middle East, where there are few rivers, although desalination is beginning to take over. About half of the total population of the United States relies on groundwater as the source of drinking water, and in the rural areas nearly everybody relies upon it. US agriculture gets around 190 billion litres per day from groundwater. Even southeast England, which is drier than much of Spain, is heavily dependent upon groundwater. Globally, it is estimated that a total of 900 km$^3$ of groundwater is abstracted every year for public use, which amounts to approximately 7% of the 12,700 km$^3$, which is the total volume of infiltrating rainfall that recharges groundwater globally each year. This may seem to imply that there is ample room for more exploitation, and indeed there is, but great care is needed, greater care than in much of the recent past.

Many cities depend heavily on groundwater supplies and much of the world's agriculture, from the American Great Plains to the Middle East, would not exist without groundwater for irrigation. As populations rise and affluence increases, especially in the emerging economies, exhaustion and pollution of surface water supplies are forcing all sectors to seek more from groundwater.

This is creating two major areas of concern: overexploitation and falling reserves on the one hand and deteriorating water quality due to pollution or saltwater intrusion on the other hand. Allied to this are secondary impacts, like land subsidence and depletion of surface waters that are hydraulically connected to the exploited aquifers.

## Global Resources

Groundwater resources are generally considered to be second only to the ice sheets and glaciers in volume, holding about 30% of all the world's freshwater supplies. However, the distribution of exploitable volumes of groundwater depends on suitable rocks as well as the present climatic water balance. Occasionally, it also depends on water balances in the past, as in North Africa and the Middle East where 'fossil' waters, thousands of years old, are now being exploited. Moreover, because it is underground and out of sight, and so difficult to measure and assess, estimates of the total volume vary more widely than for any of the world's other water stores: by nearly 8000% from a minimum estimate of around 4 million km$^3$ up to over 300 million, with an average estimate around 8 million (Jones, 1997a). This average estimate should be compared with up to just 40,000 km$^3$ in world river flow each year – the most exploited resource – and a miniscule 1700 km$^3$ actually stored in the world's rivers. Not all this groundwater is freshwater, however. Gleick (1996) estimated that there are around 10.5 million km$^3$ of fresh groundwater and 12.9 million km$^3$of saline groundwater. Nevertheless, much of this is still exploitable by applying chemical treatment to separate out the salts, e.g. using sodium carbonate, polyphosphates or sodium aluminium silicate, or else by electrodialysis. For larger volumes, full-blown desalination by reverse osmosis may be needed.

Unfortunately, because it is generally difficult to estimate the reserves, especially without sophisticated drilling equipment, groundwater is often tapped without regard for its limitations and it is frequently undervalued. This has contributed to overexploitation and ecological damage. It is also partly to blame for a tendency among surface water hydrologists to overlook it and simply assume that it is a more or less fixed storage year to year. The IPCC (2007) climate change report had little to say about it.

Groundwater is less well understood and monitored than surface flows. Rocks containing sufficient water to be exploited in bulk, 'aquifers', underlie nearly half of the total continental land area, excluding Antarctica: 30% of the global land area is underlain by relatively large, homogeneous and reasonably readily exploitable aquifers and a further 19% is underlain by less easily exploitable complex geological structures. In the remaining 50% of the continental land area there are local, patchy and relatively small aquifers, largely in near-surface sand and gravel deposits.

Martina Flörke of Kassel University has used the WaterGAP Global Hydrological Model developed by Petra Döll and colleagues at Frankfurt University to map rates of groundwater recharge globally. The results show substantial recharge in the United States east of the Mississippi and across much of Europe into Russia, as well as Southeast Asia in areas where water demand is high. However, the most extensive and actively recharging aquifers lie in areas with low population in the upper Amazon and Congo basins and in Borneo, largely beneath tropical rainforests where population levels are much lower (Fig. 1). This map also needs to be read in conjunction with that of WHYMAP in the chapter by Andrea Richts et al., this volume, which shows the distribution of suitable aquifers. The comparison confirms the view that eastern North America and Northern Europe are generally well supplied with groundwater recharge and storage, with the notable exception of the low porosity ancient 'shield' lands of northern Canada and Scandinavia. Unfortunately, Southern China, Southeast Asia and especially Indonesia have the climatic potential but lack the vital geological substrate for extensive resources.

Exploitation of groundwater is often hampered by the difficulties of assessing the level of usable supplies. A good aquifer should have a moderate to high drainable porosity, in order to hold enough *extractable* water in the voids. It should be large enough to support a reliable supply of water. And it should have sufficient permeability to allow easy abstraction of the water. The amount that is extractable is determined by the storativity or specific yield, which has to be determined from pumping experiments in wells or boreholes. Excellent numerical models like MODFLOW can be used to predict yields at new sites and to predict the impact of groundwater abstraction on groundwater levels in the surrounding area. But such models require good field data and a higher degree of information on rock types and geological structures than is often readily available. Few rocks are uniform. Water is likely to drain faster through joints and faults in the rocks than through the porous mass of rock. Such discontinuities invalidate the normal assumption of homogeneous porosity commonly made in computer models.

## World Archives of Groundwater Information

The need for better hydrogeological information was recognised at the Second World Water Forum in The Hague in 2000. The International Groundwater Resources Assessment Centre (IGRAC), an arm of the WMO in The Netherlands, was set up as a result of

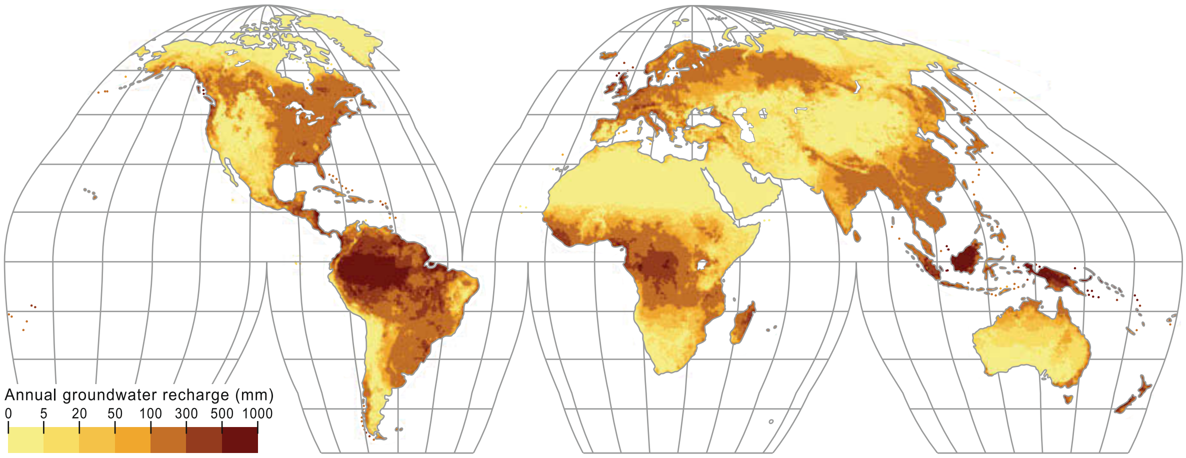

**Fig. 1** Annual rates of groundwater recharge, based on modelling by Martina Flörke using the WaterGAP global hydrological model

The Hague Declaration (www.igrac.net). IGRAC operates the Global Groundwater Monitoring Network and the Global Groundwater Information System (GGIS) which is an interactive portal. IGRAC has developed an international classification system for aquifers, which is used in the portal to allow searches at a variety of levels of generalisation. It operates Global Overview, a web-map giving access to groundwater-related aspects of countries around the world, together with a meta-database listing information on organisations, experts and international projects. Jac van der Gun et al. give a detailed account of their work in the chapter 'Geography of the World's Groundwater: A Hierarchical Approach to Scale-Dependent Zoning,' this volume.

Related work is undertaken by the German Federal Institute for Geosciences and Natural Resources in Hannover (www.bgr.de), which hosts WHYMAP, the World Hydrogeological Mapping and Assessment Programme, under the directorship of Wilhelm Struckmeier, President of the International Association of Hydrogeologists (see chapter 'WHYMAP and the Groundwater Resources Map of the World 1:25,000,000,' this volume). The main aim of WHYMAP has been to assemble and summarise groundwater information on the global scale, which it achieved with publication of its 1:25,000,000 scale map of Groundwater Resources of the World. It is also producing 1:50,000,000 special edition thematic maps, together with a resources website.

Both IGRAC and WHYMAP have had to address issues of identifying and classifying aquifers and of communicating information succinctly and meaningfully to the general public and to policy-makers. A major hurdle in this work has been to establish a common international standard for data collected under many different national schemes and at many different scales. These international databases now support the work of the UN World Water Assessment Programme (WWAP) and the World Water Development Report (WWDR), which it publishes regularly to accompany the meetings of the World Water Forum.

These archives are the first step towards understanding the global distribution and status of groundwater. They are particularly valuable for international policy-making, and they provide a first port of call for access to more detailed data stored by national hydrogeological agencies and private organisations.

## Internationally Shared Aquifers

Ever since the idea of 'water wars' was first broached at the Second UN Water Conference held in Dublin in the run-up to the 1992 Rio Earth Summit, the potential for conflict over shared water resources has been a recurrent concern in international relations. Around 60% of African rivers and 65% of Asian rivers are multinational or 'transboundary'. So are a large number of aquifers (see Figure 7 in the chapter by Wilhelm F. Struckmeier and colleagues, this volume). Wolf (1998) counted 261 major international rivers, whose basins cover nearly half of the total land area of the globe, and 'untold numbers of shared aquifers'. Although the political focus has been mainly on arguments over rights to surface waters, increasing reliance on groundwater – due to pollution, demand and climate change – is likely to ignite more arguments over subsurface resources in the future.

Already, it is clear that Israel's annexation of the Golan Heights and the West Bank in 1967 was not just about controlling the headwaters of the River Jordan. The aquifers of the West Bank have been a vital resource for Israel over the last four decades. So vital is it that 40% of Israel's water now comes from the West Bank aquifers. Prior to the Six-Day War, Israel took 60% of the water abstracted from aquifers that straddle the border between the West Bank and Israel proper. It has taken some 80% since then. Israel has withheld licences to sink new wells from Palestinians, whilst allowing the illegal Israeli settlers in the West Bank total freedom to abstract more. Pearce (2006/2007) describes how the illegal security wall built to counter terrorist attacks has also cut off many Palestinian villages and farms from their wells.

The value of the groundwater under the West Bank is a critical issue in the on-off negotiations to create an independent Palestinian state according to the American Two State Road Map. It has led Israel to negotiate a deal to potentially import water by ship from Turkey, and recently to bolster its programme of desalination. Israeli Prime Minister Netanyahu unveiled the large reverse osmosis plant at Hadera near Tel Aviv, capable of producing 456 million m$^3$ a day, and urged speedier progress with work on the large desalination plants at Ashkelon and Sorek (due in 2012), shortly before he acceded to increasing international pressure to resume peace talks with the Palestinian Authority in the summer of 2010.

Although the Israeli–Palestinian issue is the main current case of conflict over shared groundwater resources, there are many others that could emerge. The aquifers being exploited by Libya's Great Man-Made River cover some 250,000 km$^2$ straddling the borders of Egypt, Libya, Sudan and Chad. Some Egyptian scientists have expressed fears that the groundwater pumping could even reduce flow in the Nile by inducing 'influent' seepage from the river into the aquifer. Egypt has reportedly trained a special force in desert warfare in case of problems with Libya.

In response to the Ministerial Declaration of The Hague on Water Security in the twenty-first century at the World Water Forum in 2000, the Intergovernmental Council of UNESCO's International Hydrological Programme endorsed the setting up of the Internationally Shared Aquifer Resources Management (ISARM) programme in 2002. ISARM is run through IGRAC and aims to encourage cooperation between countries that share transboundary aquifers. It organises regular international conferences on the issue (see chapter by Jac van der Gun et al., this volume). Unfortunately, international law has been almost totally inadequate for solving disputes. The Helsinki Rules adopted by the International Law Commission in 1966 did not cover groundwater. The Berlin Rules adopted in 2004 have partly rectified this, but there is still no international enforcing agency (Dellapenna, 1997, 2010).

## Overdraft and Mining

The most important property of groundwater is that most of it is renewable. It is normally recharged annually by rainwater and meltwaters that seep into the ground. However, some deep groundwater bodies are essentially 'fossil'. Fossil groundwater bodies now being exploited in Libya and Saudi Arabia have received no significant recharge since the wetter pluvial period around the end of the last ice age, some 10,000 years ago. In essence, this exploitation is unsustainable; it is mining a finite resource. Libya's Great Man-Made River is a network of pipelines designed to transfer up to 2 million m$^3$ of groundwater a day from aquifers in the Nubian Sandstone system beneath the southern desert to irrigate the agricultural fields along the Mediterranean coast. How long this might be sustained is not known; another 50 years, perhaps much less. Salem and Pallas (2001) concluded that current extraction represents only 0.01% of the estimated total recoverable freshwater volume, which is more encouraging, but it does rely on a number of assumptions.

But when is mining not mining? The question is not easily answered, partly through lack of data, but more importantly because of the natural variability of the climate. One year's rainfall is rarely the same as the next, and apparently random fluctuations can create sequences of wet years or drought years: short records can produce erroneous estimates. Much of the western United States and SE Australia have been suffering prolonged droughts. In addition to 'random' fluctuations, climates tend to operate in cycles ranging from 2 to 100,000 years, maybe more, that are superimposed upon each other in bewildering combinations. These cycles are semi-regular, but each varies in intensity and duration. Many have been linked to oscillations in broad, controlling factors, like the Earth's orbit (longer term) or the Sun's activity (shorter term). The combination of these cycles and fluctuations makes estimating average recharge rates very difficult. Indeed, there is no such thing as a stable average (Jones, 2010a).

This is both good and bad. It means that groundwater resources are forever changing. It also means that *in theory* resources might be exploitable at a rate above the rate of recharge for a while 'knowing' that statistically rainfall will return to the average or above in the coming years. This is a dangerous strategy, especially in view of current evidence of systematic climate change.

Exploiting groundwater resources at a faster rate than recharge has led to widespread 'overdraft' and falling water tables in many parts of the world. Jordan and Yemen are abstracting 30% more groundwater than is being replenished and Israel is using 15% more. On the coast, this is leading to saltwater intrusions into the aquifers (*vide infra*). Inland, it is causing salinisation of the aquifer that Amman relies upon. For both Israel and Jordan, the results are highly political (*vide infra*).

Most of the western United States is suffering moderate to high levels of overdraft, from Washington State to the Mexican border, and most severely in the Ogallala aquifer beneath the Great Plains between Nebraska and Texas. Water tables have been falling in the Ogallala by a metre a year in recent decades mainly due to irrigated agriculture, and it is feared agriculture could undergo a rapid decline in coming decades. The problem began a century ago when settlers were required to show plans for irrigation schemes before property rights would be recognised. Lack of urban planning regulations has also encouraged uncontrolled urbanisation leading to severe depletion in the cities and coastal region of Texas. The water tables beneath Houston and Dallas–Fort Worth have fallen by over 122 m since the 1960s. At Tucson, Arizona, which was the largest US city dependent on groundwater until the Central Arizona Project brought water from the Colorado River in the early 1990s, overdraft caused a 50 m fall in the water table. At Baton Rouge, Louisiana, the water table fell by over 60 m following a tenfold increase in groundwater pumping between 1930 and 1970 (USGS, 2010). The conurbation of Memphis, TN, one of the largest in the world relying exclusively on groundwater resources for its public water supply, has seen water levels fall by up to 21 m. Urban–industrial users have also caused major overdraft in the Sparta aquifer in Arkansas, Louisiana, Mississippi and Tennessee. Significant overdraft problems are also reported from Chicago and the western bank of Lake Michigan and the Atlantic coast in North Carolina, Florida and Georgia.

Large areas of southern India have seen water tables fall 30 m in just 10 years and similar rates of decline have been occurring in northern China. In much of the North China Plain, the problem is profligate use of groundwater in agriculture fuelled by the low cost under the communist system (Xia, 2007). Around Beijing, where water tables have been falling by 2 m a year and most of the old city wells are now dry, the problem is urban–industrial demand. Similar problems have caused overdraft in the densely populated Hai River Basin in Northeast China (Xia, 2010).

Both China and India now have grand plans for water grids. In China's case they are already being implemented, transferring water from the well-watered south, especially the Yangtze, to the water-stressed north and Beijing (He et al., 2007). In the largest democracy on earth, India's National Perspective Plan to transfer water from the Himalayan rivers to the water-stressed south has to face numerous political hurdles before it can ever be implemented (Jones, 2010a).

A not insignificant side-effect of overpumping is land subsidence. Houston has suffered up to 3 m of subsidence. Beijing, Tokyo and Bangkok have all suffered significant land subsidence. Kazuki Mori discusses groundwater management in an alluvial plain prone to subsidence in the chapter 'Groundwater Management in a Land Subsidence Area,' this volume.

Where the aquifers are hydraulically connected to surface water bodies, overdraft can also have a deleterious effect on rivers and lakes. In such cases, overexploitation of the groundwater can be self-defeating by causing commensurate reductions in surface water resources. Over-abstraction in Tokyo has resulted in marked reductions in baseflow discharges in the smaller rivers. Similar effects can be seen around Bangkok and throughout Denmark. A study by Lvovich and Chernishov (1977) in Moscow revealed that despite the large amount of urban runoff entering the Moscow River – a fourfold increase in the central area and twofold increase in the suburbs – the discharge downstream of the city did not fully reflect this because of the overexploitation of an aquifer which is hydraulically linked to the river, causing influent seepage. In contrast, at Minsk in Belarus Kuprianov (1977) reports a very significant increase in river flow downstream of the city, because the city water supply is derived from an aquifer that is not hydraulically connected to it, so all the wastewater effluent produces extra discharge in the river.

## Improving Monitoring

Groundwater is very poorly monitored – if at all – on the ground. Monitoring has even declined in many parts of the world in recent decades. A major part of the IYPE project led by Stephen Silliman in Bénin focuses on improving monitoring of groundwater and groundwater quality (see chapter 'Overview of a Multifaceted Research Program in Bénin, West Africa: An International Year of Planet Earth Groundwater Project,' this volume).

The launch of the two GRACE satellites in 2002 has, however, proved a quantum leap. The 'Gravity Recovery and Climate Experiment' is a joint venture between, NASA, the American Geophysical Union and the German Aerospace Centre. It measures changes in the Earth's gravitational field, which can be related to changes in water distribution. Small changes in the gravitational pull on the satellites caused by the mass of water above or below the surface are converted into estimates of the changes in water distribution around the globe. The satellites provide global coverage once a month and NASA publishes some of the results on its website (www.nasa.gov).

The most dramatic result to date is the discovery of gross and rather unexpected groundwater overdraft in California, more than three times greater than officially reported by the California Department of Water Resources. The satellites have revealed one of the worst cases of groundwater mining in the world. Between October 2003 and March 2009 more than 30 km$^3$ of groundwater was abstracted for irrigation, representing a totally unsustainable annual rate of over 5.5 km$^3$. And the State government were completely unaware of the problem. Despite recent State legislation calling for a limited amount of extra groundwater monitoring, the legislation does not provide for a comprehensive monitoring system or for regulation. The Director of the Pacific Institute, Dr. Peter Gleick, says it is still a free-for-all: 'Whoever can pump it can have it, to the detriment of everyone else, our wetlands, and runoff into our rivers' (Gleick, 2009). He warns: 'California is heading for a catastrophe of huge proportions if the overdraft of groundwater continues at the same rate ... Groundwater levels will drop, the economic and energy costs of pumping will go up, and agricultural production will falter.'

GRACE also reveals massive losses of groundwater in India over a similar period, although the losses over the whole of India were only half those in the single State of California.

## Pollution and Protection

Pollution is destroying groundwater resources as much as surface waters. The Global International Waters Assessment Report found that pollution is the main water problem in a fifth of the 97 UNEP regions (GIWA, 2006). The problem has implications for both human health and the health of ecosystems. In 'Groundwater and Health: Meeting Unmet Needs in Sub-Saharan Africa,' this volume, Segun Adelana and colleagues detail some of the problems created by polluted groundwater for human health in sub-Saharan Africa. The theme is taken up by Frank Winde and Philippa Huntsman-Mapila and colleagues in 'Karst, Uranium, Gold and Water – Lessons from South Africa for Reconciling Mining Activities and Sustainable Water Use in Semi-arid Karst Areas: A Case Study' and 'Arsenic Distribution and Geochemistry in Island Groundwater of the Okavango Delta in Botswana,' this volume.

## Nitrates

Nitrate levels rose dramatically in many European rivers and aquifers during the latter half of the twentieth century as a result of artificial fertilisers. This was largely due to the EU Common Agricultural Policy, which by guaranteeing a minimum price for agricultural products encouraged large-scale applications. In Britain, the use of inorganic nitrate fertilisers increased threefold between the 1960s and the 1980s. Yet more nitrogen was added by increased volumes of animal urea. By the 1980s, levels in some East Anglian rivers, like the Great Ouse, had risen to almost the WHO recommended limit of 10 mg N as nitrate per litre (Roberts and Marsh, 1987). Relatively high levels are also found in parts of the Indian subcontinent, notably Gujarat, West Bengal and Bangladesh, as well as in the southwestern United States.

In 1991, the EU introduced the *Directive Concerning the Protection of Waters Against Pollution Caused by Nitrates from Agricultural Sources*, introducing the designation of vulnerable zones in order to protect aquifers used for drinking water. Member states identified nitrate sensitive aquifers and introduced groundwater protection zones, limiting applications. Britain designated the River Dee Basin in North Wales as its first integrated surface and subsurface water protection zone in 1995 and has since designated many more.

The reason for concern has been the fear that nitrates are responsible for the infantile condition called Blue Baby Syndrome or methaemoglobinemia. However, although the WHO recommended limit is based on this, the medical evidence is not clear-cut (Jones, 2010a). An alternative strategy to limiting fertiliser applications has been proposed based on observation of natural denitrifying processes. If the soils and shallow floodplain deposits are allowed to remain wet and undrained, natural denitrifying bacteria reduce the nitrate to nitrite and thence to nitrogen gas, which is released into the atmosphere. According to this proposal, the solution is to leave the riparian zone untouched to allow the natural removal of nitrates (Burt and Haycock, 1992).

The very same properties that make groundwater a stable supplier of water also make aquifers vulnerable to long-term pollution. The slow rate of turnover means that it can take years, even decades, to cleanse an aquifer once polluted. Rang and Schouten (1988) coined the term 'hydro-inertia' for this tardy response after studying two aquifers in southern Limburg, where applications of nitrogen fertiliser had risen as high as 540 kg/ha/year. Table 1 shows the differences in the response of streams fed by aquifers with short and long retention times, the plateau sands and gravels and the Margraten limestone, respectively. Even if strong measures were taken to prevent nitrate leaching into groundwater by conforming to EU restrictions on the application of nitrate fertilisers, concentrations in the springs will continue to rise. Rang and Schouten's calculations suggest that it would take over 50 years for the concentrations in streams fed by the Margraten limestone unit to start to fall, with drainage from the plateau gravels reaching peak concentrations in the mid-1990s and the limestone peaking in the 2050s, and springs only returning to the EU drinking water standard of 50 mg nitrate per litre (roughly equivalent to the WHO 10 mg of nitrogen standard) by 2025 and 2080, respectively.

## Arsenic

While controls are beginning to limit nitrate pollution in Europe and North America, arsenic is becoming a far greater concern worldwide than nitrate ever was. The medical evidence is also far more certain and serious, involving cancers, gangrene, hyperkeratosis and danger to the liver and nervous system. Levels of arsenic in excess of 0.01 mg/L have been recorded in parts of the Seine and upper Rhone basins and in the Netherlands, but the real concern is for drinking water derived directly from aquifers.

A world survey undertaken by the British Geological Survey in 2001 found arsenic-affected aquifers on every continent: notably the Chaco-Pampean Plain in Argentina, northern Mexico, the western United States and Minnesota and the Great Hungarian Plain. China has large areas of affected aquifers in Xinjiang, Inner Mongolia and Shanxi provinces. Taiwan and the Lower Mekong Basin are badly affected, as is the Ganges delta region from West Bengal to Bangladesh. Philippa Huntsman-Mapila and colleagues take up the story in 'Arsenic Distribution and Geochemistry in Island Groundwater of the Okavango Delta in Botswana,' this volume with particular reference to the calamitous arsenic pollution that has afflicted the town of Maun in Botswana's Okavango delta region. Some nine other cases are linked to rising geothermal waters, including the French Massif Central, the Aleutian Islands, Yellowstone National Park, Kamchatka and Kyushu in Japan. Yet another set of problem areas is related to mining operations, e.g. in southwest England, the Ashanti region of Ghana, Halifax Nova Scotia and Fairbanks Alaska.

Current research is pointing to recent changes in water management as the source of the problem in many parts of the world. A key piece of evidence for this is that millions of people in areas of Bangladesh now badly affected drank well water for thousands of years with little evidence of toxic effects until the late twentieth century. The problem there appears to be linked to a dramatic increase in the use of groundwater as a supposedly safer source of drinking water and as a major resource for the expansion of irrigated agriculture. It was not until the 1980s in West Bengal and 1990s in Bangladesh that medical records began to show a significant rise in pathological symptoms, even though millions of tube wells were installed to abstract groundwater in Bangladesh before the 1970s. From the 1960s onwards, the World Bank was a principal promoter of the switch to groundwater and funded thousands of tube wells for irrigation to support the rise in agricultural production fuelled by the Green

**Table 1** The effect of aquifer retention time on output of nitrate, sulphate and chloride in spring-fed streams in South Limburg, after Rang and Schouten (1988)

| Hydrogeological unit | Aquifer | Time to peak concentration, no restrictions (years) | Time to peak with EU limit of 50 mg/L (years) | $NO_3$ (mg/L) | $SO_4$ (mg/L) | Cl (mg/L) |
|---|---|---|---|---|---|---|
| Margraten plateau | Limestone | 80–100 | 60 | 31 | 37 | 17 |
| Central plateau | Gravel/sand | 20–30 | 10 | 73 | 86 | 39 |

Revolution. A severe outbreak of cholera in south Bengal in the 1960s and the worsening biological contamination of surface waters in the late twentieth century added to the rush to exploit 'safer' groundwater resources.

As a result of overexploitation, water tables began to fall allowing oxidation of the deltaic deposits. Oxidation of pyrite, arsenopyrite and clay minerals with arsenic adsorbed on their surface causes arsenic to be released. When the water table rises again, the arsenic enters the groundwater. It is also possible that reduced river flows have added to the problem. Diversion of Ganges waters to Kolkata (Calcutta) from 1975 onwards by India's Farakka Barrage and reductions in the discharges of the Tisha and 28 other transboundary rivers crossing into Bangladesh from India may have been reducing groundwater recharge in the delta.

Although the oxidation hypothesis is the most widely accepted, two other hypotheses have been advanced, one also related to water management and the other to agriculture. The hydrological hypothesis suggests that overirrigation creates persistent anaerobic conditions, which produce a chemically reducing environment, and in organic-rich clayey sediments this leads to the dissolution of iron oxyhydroxides containing sorbed arsenic, possibly assisted by iron-reducing bacteria. The agricultural hypothesis centres on nitrate fertilisers, which can oxidise sulphate minerals and release sorbed arsenic. As the enormity of the problem has been realised some communities in the Bengal Basin have begun to revert to using surface waters. Others have been introduced to simple home filtration systems, using buckets filled with sorbent materials, like laterite, or oxidising substances like ferric chloride and potassium permanganate and cloth filters. Ali et al. (2001) report such systems capable of reducing arsenic concentrations to less than 20 μg/L, even with water originally containing up to 500 μg/L.

## Uranium

As the world turns again to nuclear power, this time as a supposed solution to global warming, one hazard that is being largely overlooked is pollution from mining. Frank Winde has exposed the problem in South Africa almost single-handedly over the last two decades. He explores the problems in detail in 'Karst, Uranium, Gold and Water – Lessons from South Africa for Reconciling Mining Activities and Sustainable Water Use in Semi-arid Karst Areas: A Case Study,' this volume.

The problem is that mining operations are mainly conducted well away from the areas or indeed the countries where the material is used to fuel power stations. The recipient countries are well aware of the issues surrounding 'safe' disposal of spent fuel, but are either ignorant or unconcerned about the problems facing the miners and their communities. Winde's campaigns through his many sound and detailed scientific publications have begun to change official attitudes in South Africa. But it will take time to permeate around the world and there are powerful interests, not least countries with nuclear weapons, that may wish to ignore the issue as they did with the question of disposal.

South Africa is now reopening mines mothballed in the late twentieth century as nuclear power fell from favour. In 2007, it declared uranium a 'strategic mineral' and the government's Nuclear Fuels Corporation, the largest continuous producer of uranium concentrate in the world, estimates that 25 new mines will be needed by 2020. High levels of leukaemia and related blood anomalies have been reported from the Northern Cape where drinking water taken from a borehole is high in uranium (Winde, 2010). Much of the mining pollution identified by Winde occurs through leakage and infiltration from the waste material held in tailings deposits and slimes dams. This enters the streams either directly or after first draining into the groundwater.

Not all uranium pollution comes from mining uranium. Gold mines are another prime source. Uranium is commonly found in association with gold and gold mining activities in South Africa have a much longer history. Winde has studied the case of the Wonderfonteinspruit stream near Potchefstroom in South Africa's North West Province for many years (Winde, 2006). Here, groundwater from the dolomitic rocks of the West Rand gold mining area is feeding radioactive pollution into a stream, which is a source of drinking water for some of the poorer communities around the town. Study of the health effects on the communities is hampered by the fact that many of the people are migrant miners: their short sojourn in the area may be a salvation for them, but it also makes it difficult to trace the effects.

The pollution is not only due to leakages and infiltration from the tailings dams. Dewatering of the mines also brings polluted groundwater to the surface, where it is subject to a chemically more aggressive, oxidising environment.

In Canada, the north shore of Lake Athabasca in the Mackenzie Basin is heavily contaminated with uranium from buried and ponded mine tailings. Centred on Uranium City, the area once had 52 pits and 12 open cast mines extracting gold and uranium. Operations were largely closed down in the early 1980s, but as demand for both metals has recovered and prices have increased, operations restarted in 1995 around the aptly named McClean Lake. The work is supposed to be cleaner now and the McClean Lake operation received an ISO 14001 environmental management certificate in 2000. However, in 1998 one mining company was convicted of contaminating the environment and not reporting it.

The question of safe disposal of waste from nuclear power plants also remains largely unresolved. In the UK, the official body set up to solve the issue, Nirex, spent decades searching unsuccessfully for a secure deep burial site where there is no risk of contaminating the groundwater. Nirex was disbanded and Britain now exports waste to Gorleben in Lower Saxony where most of the German radioactive waste is stored. However, in 2010 fears emerged that some storage sites in Germany may not be as secure and watertight as they should be. Nuclear waste buried in a 750 m deep disused mine in Asse, Lower Saxony, may be leaking into the groundwater. It is estimated that around 12,000 L of water is leaking into the mine which is said to hold 100 tonnes of uranium, 87 tonnes of thorium and 25 tonnes of plutonium. Plans have been laid to transfer canisters to another mine at Schacht Konrad. Much of the nuclear waste generated in Germany between 1967 and 1978 was buried in a depopulated zone near the East German border when safety standards were less strict and political considerations meant that inventories were kept vague. One recent suggestion is to export waste to eastern Siberia. The EU is now considering a collective high-level waste storage facility in one of the new member states in Eastern Europe and giving them monetary compensation.

As Dr. Winde reports, the recommended ‘safe’ levels of uranium pollution have been reduced over the years, but the scientific basis for the recommendations is still inadequate, mostly relying on analyses following Hiroshima, and the question remains: Is any concentration safe if ingested over a long enough period? The effects of ingestion are likely to be quite different from external exposure to radiation.

## Oil and Gas

The search for fuel is being radically ratchet up by the rising price of gas and petroleum. Rivers, lakes and shallow groundwater bodies are being severely polluted by opencast mining of the Athabasca tar sands in Alberta and seepage from vast areas of slimes reservoirs. The Oil Sands Regional Aquatics Monitoring Program (RAMP) was set up in 1997 to monitor water quality and environmental impacts. However, in September 2010, Canadian Environment Minister Jim Prentice appointed an independent panel of scientists to investigate the continuing pollution of the Athabasca River after seeing photographs of deformed fish and receiving a report showing high levels of lead and mercury in the riverwater. As much of Alberta’s newfound wealth over the last decade has come from the mining operations, he overruled the provincial government, insisting that water management is a federal responsibility and rejecting requests for participation from the Alberta government. The author of the censorious 2010 report, Dr. David Schindler, criticises RAMP as totally inadequate. Film director James Cameron (of *Avatar* and *Titanic* fame) went further, saying that the oil sands development is unfettered and environmentally appalling, and he publicly lobbied governments and the UN Permanent Forum on Indigenous Issues, as the local First Nation population, the Dene and Cree people, have been complaining for years about increased incidence of cancers and other health problems affecting both people and the fisheries.

The latest threat comes from the method known as ‘hydrofracturing’ to extract oil and gas from deep bedrock. ‘Fracking’ involves injecting tonnes of water into shale bedrock to open up fractures, together with sand and chemicals to dislodge the hydrocarbons so they can be flushed out to the surface. Between 11 and 30 million $m^3$ of water may be injected into each well, of which only a half to a third is recovered, all heavily polluted with oil and chemicals. Some of this may even get into public water supplies. In 2010, a documentary film called *Gasland* featured a man putting a lighter to his kitchen water tap and flames shooting out.

The technique has been developed in Texas over the last two decades. It is now set to spread more widely as the price of oil and gas is rising steeply. Toreador of Texas has licences to explore over 750,000 km$^2$ between St Dizier and Montargis in the Paris Basin, where they believe the organic-rich sedimentary rocks could yield 50,000 barrels a day within a few years. The total yield from the Paris Basin could reach 65 billion barrels, making it nearly double Nigeria's 36 billion. Poland could hold 50% of Europe's gas reserves, and the government is keen to develop the resource in order to reduce dependence on Russia's fickle Gazprom. Conoco has begun test drilling in Poland in collaboration with Three Legs Resources from the Isle of Man. Germany, Hungary and Sweden are likely to follow. In the UK, Cuadrilla Resources has struck gas in shales near Blackpool. These developments could have huge implications for water resources in Europe and elsewhere.

A report produced for New York City in 2009 expressed grave concerns about the damage that expansion of hydrofracturing to extract oil from the Marcellus Shale in the Catskill Mountains and Upper Delaware Basin could cause to the city's water supply, particularly through contamination of groundwater supplies by the toxic chemicals. As a result, politicians urged the government to ban fracking and the Federal Government passed a FRAC Act in 2009 putting the EPA in charge of policing the practice. It remains to be seen how effective this will be.

## Salinisation of Surface Waters

Resurgence of saline groundwater is responsible for serious pollution of streams in the Ebro Basin, northern Spain. Here, expansion of the irrigated area as part of Franco's post-war 'regenerationist thrust' led to a steady rise in dissolved salt concentrations in the rivers. As the area under irrigation expanded from 420,000 ha in 1945 to 702,000 ha at Franco's death in 1975, the salinity of the Rio Ebro increased from 600 mg/L to ca. 800 mg/L, and it continued to rise to nearly 1000 mg/L by the end of the 1990s: an average rise of 10 mg/L per annum. The problem is caused by excess irrigation water seeping into the underlying evaporite rocks, especially the gypsum beds. As the return water from one irrigation system is abstracted from the rivers by irrigation systems downstream, the concentrations increase. On the lower Rio Gallego, just north of Zaragoza, farmers experienced gradually falling fertility as the riverwater slowly salinised the soil and there were fears that some farms might become non-viable by the turn of the millennium. Since then, practices have improved and the latest extension of irrigation – into the Monegros southeast of Zaragoza, an area characterised by dolines and defunct salt factories – is more frugal and based on timed sprinklers. Even so, there have been serious questions as to whether any irrigation at all is prudent in such an environmentally sensitive area.

Ironically, there are now moves to use seawater for irrigation. Experiments have been carried out in China, Japan and the United States with reportedly successful results. Some food crops have been grown, such as tomatoes and peppers, but there may be a wider application for biofuel crops. In California, salt-tolerant grasses have been successfully employed on golf courses. However, the possible implications for groundwater do not appear to have been investigated.

## Groundwater and the Sea

Saltwater intrusion is an increasing problem in coastal aquifers, especially where overdraft is reducing the protective back pressure of the freshwater body. It is already critical on some oceanic islands, especially islands built of coral or porous volcanic rocks. The worst-case scenario is on small, low-lying islands with no rivers. Kliot (2010) lists the most severe cases where a small lens of fresh groundwater is floating on saltwater. Excessive withdrawals have critically reduced the freshwater lenses in the Bahamas, Kiribati, Maldives, Marshall Islands, Nauru, Niue, Northern Cook Islands, Seychelles, Tonga and Tuvalu. Once saltwater contamination has occurred, it can take years to clear. Overexploitation has also caused significant intrusion on many Mediterranean islands and along mainland coasts. The Balearics, Cyprus, Malta, Rhodes, Sardinia and Sicily are all suffering.

The coastal aquifers of Israel and Gaza are badly affected. In the case of Gaza, the issue is critical because of the paucity of surface water and the Israeli blockade and ban on the importation of cement and steel to repair the water infrastructure destroyed during the Israeli offensive in 2009. For Israel it is also a factor that has led it to withdraw more freshwater from the rivers and aquifers of the Jordan Valley.

Sea level rise is going to aggravate the situation. Using the A2 SRES scenario for global warming (IPCC, 2000), Ranjan et al. (2009) calculated that fresh groundwater resources will be significantly reduced throughout the coastal areas of the Caribbean, the Gulf of Mexico and Central America from the southern United States to northern Brazil, the Mediterranean, Australia, the Yellow Sea and much of Africa. Some saltwater intrusions may be caused by the increased pressure from seawater. Others may result from reduced recharge of the freshwater lenses as rainfall is reduced and/or drought events become more frequent or severe. Kliot (2010) notes that El Niño episodes during the last two decades have reduced precipitation by as much as 87% in the western Pacific and that droughts are frequent and desertification is occurring in Mauritius, Madagascar and the Seychelles. Hughes and colleagues discuss the problems for modelling groundwater response in 'Climate Change and Groundwater,' this volume.

An interesting case of environmental engineering in the Netherlands has also been responsible for saltwater intrusion. When the Rhine Delta Project was begun after the devastating sea floods of February 1953 that inundated 200,000 ha and killed nearly 2000 people, the aim was to build solid barriers across the seaward outlets of the distributary channels. Subsequent re-evaluation of the environmental impact has led to a gradual relaxation of the solid barrier philosophy. Allowing saltwater into Lake Grevelingen in the 1980s, in order to establish oyster beds to replace the valuable beds destroyed by pollution in the Eastern Scheldt, caused saltwater intrusion into groundwater sources used by farms and villages around the lake. The Rijkswaterstaat had to formulate a plan to move the groundwater pumping sites further back from the lake.

Saltwater intrusions are a major current problem and likely to increase both because of increasing public demand for water and through climate change. Yet there are two other issues the importance of which is only just beginning to be realised. One is potentially good. The other presents a new perspective on a known hazard.

## Groundwater and Sea Levels

Sea level rise is one of the most feared consequences of global warming. The IPCC (2007) report estimates that average global sea level will rise by 18–59 cm by 2100, depending on the economic and emissions scenario used. A rise of just 40 cm in the Bay of Bengal would force up to 10 million inhabitants of Bangladesh to become refugees. Many of the world's greatest cities are also vulnerable. Under the more extreme scenarios, up to 14 million people in Europe would be at risk and there would be major economic costs. One estimate suggests that the cost of protecting the coastal regions of the United States could reach $156 billion.

The commonly accepted view is that thermal expansion of the oceans will be responsible for around half of the projected rise and the melting of small or mountain glaciers for most of the remainder. It has been widely assumed that the responses of the polar ice sheets would largely balance out – the melting of the Greenland ice cap being countered by increased snowfall in Antarctica. This was never a sound hypothesis and it is now clear to many that that assumption was erroneous. Any extra snowfall in Antarctica caused by evaporation from warmer seas is only likely to affect the continental periphery, as the atmospheric high pressure system over the South Pole is not conducive to snowfall formation and the surface winds blow out from the centre of the continent.

However, Jones (1997a, 27) questioned whether 'human exploitation of deep groundwater, which is being returned to the active branch of the hydrological system' might also be playing a part. A recent study seems to offer the first quantitative evidence to support this and highlights the overlooked contribution that groundwater overdraft might have on sea level rise. Wada et al. (2010) used the IGRAC database on national groundwater abstraction rates, together with estimates of water demand based on population densities and the location of irrigated land, to produce a world map of groundwater abstraction. They then compared this with a global map of groundwater recharge to estimate overdraft. Assuming that most of the abstracted groundwater ends up in the sea, they calculate that between 1960 and 2000 groundwater abstraction increased from 312 $km^3$ a year to 734 $km^3$ and groundwater depletion rose from 126 $km^3$ to 283 per year. On this basis, they estimate that overpumping has raised global sea level by an average of 0.8 mm per year or about a quarter of the total 3.3 mm p.a. estimated by the IPCC.

This is a highly significant sum. It would mean that melting ice is only responsible for just over a quarter of sea level rise. However, the authors may only be seeing half the real picture. Another recent study by surface water hydrologists focuses on the effect of reservoirs. Chao et al. (2008) calculate the volume of water that has been retained in reservoirs as dam building has accelerated over the last 50 years. They conclude that reservoirs have withheld a cumulative total of 10,800 km$^3$ over that period, which would have reduced sea level rise by 30 mm. That would amount to a reduction in sea level rise of 0.6 mm per year. They conclude that this means that the real or 'natural' rate of sea level rise is greater than estimated by the IPCC (2007).

In fact, both sets of authors are seeing only half the story. It demonstrates some of the complexity of the world water system. It is good to uncover this complexity. Ironically, however, groundwater depletion and reservoir construction almost perfectly cancel each other out – at least over the period analysed in these studies. But what of the future? The number of new dams being built peaked in the 1970s and by the 1990s it had fallen below that of the period immediately following World War II, albeit with larger dams. Numbers are actually reducing in the United States, partly due to environmental and social objections. Dams are actually being demolished in America and Spain. What if the rise in volumes of impoundment stalls? This would destroy the current balance. There is even the possibility of groundwater depletion rising whilst impoundment falls, given the trend in some parts of the world to rely more on groundwater, in part because of polluted or inadequate surface waters. Wada et al. (2010) identify India, Pakistan, the United States and China as the main areas of greatest groundwater depletion. The Asian countries are still big dam builders, but for how long?

## Exploitable Leaks to the Sea?

The second, more hopeful issue is the possibility of exploiting groundwater currently 'going to waste' in the sea. Back in 1970, R.L. Nace of the US Geological Survey attempted to calculate the volume of water draining directly from groundwater into the sea, which had largely been overlooked till then. He called it 'runout'. He based his calculations on estimates of the permeability of coastal rocks. The results suggested that it is insignificant in global terms, at only 7000 m$^3$/s (221 km$^3$/year): barely 1% of global river flow. However, when Speidel and Agnew (1988) revisited the issue their conclusion was rather different. Their figure was 12,000 km$^3$/year, which *is* globally significant: equivalent to a quarter to a third of net atmospheric transport of water vapour from the ocean to the land. Their view is corroborated by Burnett et al. (2006) in their review of a variety of methods that may be used to quantify submarine groundwater discharge.

As Dragoni and Sukhija (2008) observe: 'All this water is lost to the sea, often of acceptable quality, and research to improve the measurement and recovery of it should be strongly enhanced'. However, if this loss is through diffuse seepage, then it will be virtually impossible to harness. But submarine springs are different and evidence of their existence is increasing, most notably in karstic regions. One such spring off the northeast coast of Florida near St Augustine discharges 40 m$^3$/s (1.26 km$^3$/year) and is already the subject of a proposal to harness it. A 1995 survey identified 15 submarine springs off the Florida coast, mainly on the Gulf coast between Wakulla and Lee. Some freshwater resurgences have been found up to 120 km off the Florida coast. The most valuable springs are the deep-seated 'Floridan springs', which are fed from a vast aquifer, and maintain a steady discharge even through droughts, in contrast to the shallow springs. They promise both high yields and stability of discharge and could be particularly valuable to a state like Florida that is suffering water stress due to the rise in population and water demand and its vulnerability to droughts like those of 2001 and 2007, which severely stressed surface water systems. Rising demand has already caused severe groundwater overdraft in much of central and southern Florida, in tandem with reductions in recharge through urban paving and drainage of wetlands. To meet this demand whilst easing pressure on the aquifers, Florida opened the largest desalination plant in America in 2007 on Tampa Bay, capable of processing 190,000 m$^3$/day, and the state has the highest number of desalination plants, some 120: three times more than Texas and four times California. But unlike exploitation of land-based aquifers, tapping submarine springs is merely capturing a natural wastage. Provided pumping is not involved, it is capturing natural drainage and will not affect the water table on land.

There is similar potential along much of the Mediterranean and Black Sea coasts, notably in Croatia, Crete and the south of France: one off Montpellier yields 50 L/s. Kondratev et al. (1999) report that during the water shortage in Sevastopol in the Crimea in 1993, Ukrainian scientists investigated the possibility of tapping some of the local submarine freshwater springs. One such spring on Cape Aiya was discharging 30,000 $m^3$/day (1 $km^3$/year) of low salinity ($5.5^0/_{00}$) water.

Water might be collected from submarine springs using flexible, transportable pods, rather like the 'water bags' or 'cigars' used to transport potable water to some Greek Islands. Alternatively, it might be captured and piped directly onshore. Although the technology is yet to be fully developed, the approach offers the prospect of a new and environmentally sound source of freshwater, without increasing groundwater overdraft.

## Groundwater Reservoirs

In contrast to submarine springs, artificial recharging of aquifers has been practised for a while and has increased markedly in recent years. Aquifers can make very efficient reservoirs as they lose little or nothing through evaporation. This makes them preferable to surface reservoirs in warm climates. The overburden also provides natural protection against many sources that pollute surface waters, like faecal material and pathogens. It can even be used as a means to clean up poor quality surface water, by pumping polluted water in and abstracting it again some distance away.

It is also relatively cheap and cost-effective, with few costs for construction and maintenance. Where and when there is spare storage capacity in an aquifer, it can be used to store surplus surface water until it is needed. It may also be used as an efficient means of water transport, pumping water in one borehole and abstracting from another elsewhere. It can be especially useful when demand is very seasonal. The Algarve is a good example of a warm, dry climate combined with highly seasonal demand from tourism: a resident population of just over 400,000 and 6 million tourists a year. Deputy leader of the IYPE Groundwater SIT, João Paulo Lobo Ferreira, and colleagues describe the various techniques of artificial groundwater recharge and give details of Portugal's recharge programme in the chapter 'Groundwater Artificial Recharge Solutions for Integrated Management of Watersheds and Aquifer Systems Under Extreme Drought Scenarios,' this volume.

Over the last quarter century, artificial storage and recovery schemes have proliferated in the United States. The Everglades Restoration scheme in southern Florida is injecting high-quality surface water, which would normally discharge into the sea during the rainy season, into more than 300 boreholes in order to restore the Upper Floridan Aquifer that has become brackish due to overpumping. The method has been used in Israel as an efficient means of storing and transferring water at least since the 1970s. It is also used in southeast England. The Great Ouse Groundwater Scheme was also developed during the 1970s and subsequently incorporated into the Ely Ouse Essex Water Transfer Scheme, transferring water from East Anglia to the Thames Basin (Hiscock, 2005). Under the North London Artificial Recharge Scheme in the chalk and Tertiary sandstone of the Lea Valley, over 20 boreholes are used to inject water during periods of riverwater surplus and the same boreholes are reused to abstract the groundwater during low flows in summer. Artificial recharge was introduced on the Lambourn–Kennet river system to sustain river flows during the summer, after the Thames Groundwater Scheme, which was introduced in the 1970s to pump water out of the chalk to top up levels in the River Thames, proved environmentally damaging. Another ecological application is described by Boeye et al. (1995) in Belgium, after they observed that recharging groundwater from a canal reduced the acidity of a wetland, transforming a bog into a rich fen.

Artificial recharge is also being used as a means of purifying surface water for public drinking water supplies. Early experiments were undertaken in the late twentieth century in the floodplain of the Rhine in Germany when the riverwater was at the height of its pollution, pumping riverwater into the floodplain deposits and pumping the filtered water out some distance away.

## Putting a Value on Groundwater Resources

Putting a price on groundwater resources could help more formal cost-benefit analyses to be made. It might also help conservation. One way to cut demand is to increase tariffs. This is a common instrument for drinking water supplies, but is little used for the agricultural use of groundwater, where the water does not generally require treatment and normally only costs a few cents per cubic metre at most to pump up.

Professor Wilhelm Struckmeier has tried to assess the value of groundwater to the world economy by assigning it a notional global value of €0.5 per cubic metre, based on average European values which typically range between €0.8 and €1.4. The result is revealing (Table 2).

Of all the major underground resources, groundwater tops the list in terms of the quantity used annually and by his calculation it is second only to oil in terms of monetary value. Even so, this is still only a crude indicator of its value to humanity. It is an estimate of what might be charged for it, not of its value to life or as the basis for economic activity. Nevertheless, even the value assigned here is higher than the price in many parts of the world, including regions where groundwater is being overexploited. Raising tariffs in some of these regions could be a valuable aid to controlling consumption.

## Groundwater and Nature

Valuable as groundwater is to us as a source of water, this is far exceeded by its value to nature. It is a truism that groundwater is what keeps the rivers flowing when the rain has gone. This was so evident to the ancients that most natural philosophers discounted rainfall as a source of river flow until the first hydrological experiments by Pierre Perrault and Nicolas Papin proved otherwise in the seventeenth century.

Recent scientific attention has been focusing on the hyporheic zone, the area of riverbed where groundwater and riverwater are exchanged (USGS, 1998; Environment Agency, 2005). Established views have tended to study rivers and groundwater as separate entities. The European Water Framework Directive (2000) is now seeking to establish a more integrated approach to river and groundwater management as a major part of its aim to make member states bring all water bodies into ‘good ecological status’ and ‘good chemical status’ by 2015. To meet this challenge, the English Environment Agency is funding hyporheic zone research. As the EA have stated: ‘our knowledge of processes that occur at the interface of these systems is poor.... Hyporheic processes are commonly overlooked in environmental risk assessments, but hyporheic and riparian zone attenuation reduces pollutant fluxes to some rivers.’

Groundwater is also important in the wider landscape, sustaining many wetlands. Loss of wetlands is often a factor reducing groundwater recharge, and some wetlands are now being artificially reconstructed

**Table 2** Volume and value of groundwater production compared with other major natural resources

| Resource | Annual production (million tonnes) | Total value (million €) |
|---|---|---|
| Groundwater | > 600,000 | 300,000[a] |
| Sand and gravel | 18,000 | 90,000 |
| Coal | 3640 | 101,900 |
| Oil | 3560 | 812,300 |
| Lignite | 882 | 12,300 |
| Iron | 662 | 16,400 |
| Rock salt | 213 | 4500 |
| Gypsum | 105 | 1500 |
| Mineral and table water | 89 | 22,000 |
| Phosphate | 44 | 3000 |

[a] At a notional value of €0.5/m$^3$

Source: Struckmeier et al. (2005)

as a means of increasing recharge (see chapter by Kevin M. Hiscock, this volume). The United States lost nearly half its wetlands during the last two centuries; the Netherlands and Germany lost a similar proportion of theirs just in the last 50 years. Wetlands may act as points of recharge, resurgence or both. Programmes initiated over the last decade or so to restore wetlands – in the Everglades, the upper Missouri and Mississippi basins, the Netherlands, England and elsewhere – have had varying aims, largely flood control or increasing biodiversity, but many will also be enhancing groundwater recharge, whether intentionally or not. The elaborate water management system operated in the South Florida Water Management District and the restoration of wetlands in adjacent areas of the Everglades is in part designed to maintain water head in order to recharge the vital Biscayne aquifer that has been so impacted by increasing public demand for water.

On a detailed level, Fig. 2 shows a case where the resurgence of shallow groundwater on a hillside is responsible for altering the development and distribution of both soil and vegetation – a small example of groundwater resurgence increasing biodiversity (Jones, 2004, 2010b).

In the chapter 'Linking Runoff to Groundwater in Permafrost Terrain,' this volume, Ming-ko Woo describes another case of groundwater–surface water interaction in the permafrost landscape of northern Canada. This is an environment that is set to change dramatically with the advent of global warming, melting the permafrost, increasing groundwater movement and exchange (Woo et al., 2010) and in the process releasing more methane and perhaps also clathrates, methane hydrates. Clathrates are peculiar compounds that have a shell of frozen water around a core of methane. There are huge quantities frozen in the permafrost at high latitudes. Immediately after the frozen ground melts, they become unstable and there are concerns that this could lead to a strong positive feedback to global warming (Lipkowski, 2006). Destabilisation of methane hydrates is believed to have been a major mechanism of global warming at the end of the last ice age.

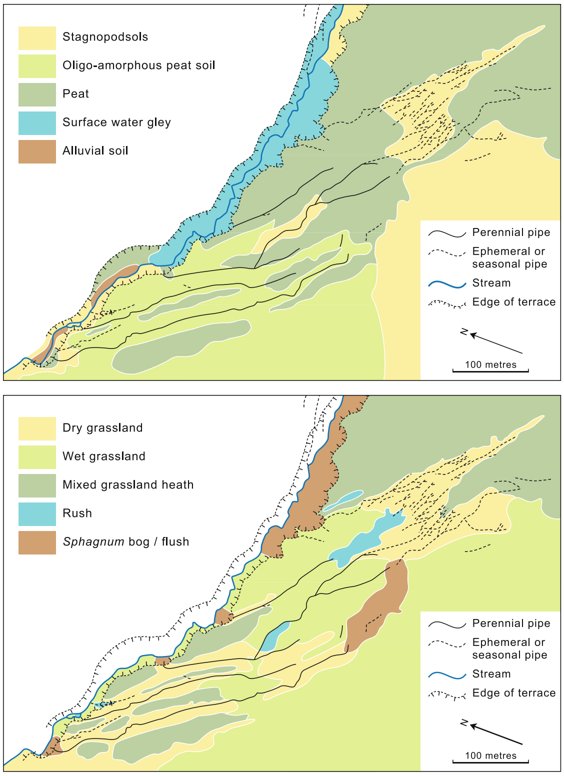

**Fig. 2** Groundwater resurgence in mid-slope sustains flow in natural soil pipes that drain downslope from the mid-slope bog area, marked by *Juncus* (rush) and *Sphagnum* moss. The patterns of soil (*top*) and vegetation (*bottom*) reflect the lines of drainage (Maesnant, Wales, after Jones, 1997b)

## And Climate Change?

Global warming is going to affect rates of groundwater recharge in many parts of the world. Hughes and colleagues discuss the issues in detail in the chapter 'Climate Change and Groundwater,' this volume. At this juncture, however, it is worth noting that modelling done by Döll and Flörke (2005) using the WaterGAP global hydrological model, which was used in the IPCC (2007) assessment, has given some initial pointers. It also reveals some of the large uncertainties that exist at this stage. The authors used the climatic outputs from the British HadCM3 and the German ECHAM4 General Circulation Models for the 2050s according to the assumptions of the A2 and B2 scenarios (IPCC, 2000). A2 is one of the more extreme scenarios and is generally taken to represent a reasonable 'worst-case scenario', with rapid grow in population and world economies resulting in one of the higher estimates of greenhouse gas concentrations. B2 is much less extreme, assuming local solutions to environmental sustainability, an intermediate level of economic growth and population increases much lower than A2. The results suggest that there will be particularly marked reductions in groundwater recharge in Southwest Africa, Northeast Brazil and parts of the Mediterranean. However, the differences between the GCMs are greater than the differences between the two emissions scenarios. This clearly should not be, and it underlines the continuing limitations of climatic modelling, even for third and fourth generation GCMs.

## Managing Groundwater Sustainably – Some Conclusions

Groundwater is threatened from many sources as never before: from increasing demand for water as populations and affluence grow, from intensified agriculture driven by human demand and the profit motive, from industry and mining, and from climate change. Kevin Hiscock reviews the challenges ahead in the final chapter of this book.

International organisations like IGRAC, WHYMAP and ISARM are monitoring the situation, feeding policy-makers and the scientific community with sound facts and advice. The new GRACE satellites are revealing more about groundwater overdraft than was ever possible by traditional methods. Scientists are also beginning to model the possible effects of global warming, but this was a major omission in the IPCC (2007) report. Wada et al. (2010) suggest that groundwater depletion was excluded from the IPCC assessment because of the high uncertainty surrounding estimates of the rate of depletion, and their own work now goes some way towards dispelling some of that uncertainty.

However, how to manage groundwater sustainably remains a critical and difficult issue in many situations. The lack of measurements can be compounded by the often complex physics of groundwater movement. It may take a considerable time before an exploited groundwater system achieves equilibrium, that is, when pumping and recharge rates balance. The act of abstracting groundwater can initiate changes in the aquifer that take time to settle down, maybe years, and the final yield from the aquifer may be substantially different from the one estimated beforehand, especially if dewatering results in compaction. The extent to which abstracting groundwater may induce influent seepage from rivers and stream which then feeds the aquifer may also complicate the situation. Because of this, John Bredehoeft and colleagues at the USGS referred to the use of pre-development water budgets as a method of assessing the available groundwater resources as the 'water budget myth' (Bredehoeft et al., 1982). They also point out that the actual placement of wells relative to the groundwater body can affect yields and the time taken to reach equilibrium. According to them, some groundwater must be mined before the system re-establishes a new equilibrium. But long-term mining, as practised in the western United States, the Middle East and North Africa, is, of course, unsustainable. Unfortunately, Bredehoeft and colleagues note that in many States, like Nevada, the laws relating to exploiting groundwater do not take adequate account of these concepts and the likely difference between pre-development and post-development resources (Bredehoeft et al., 1982; Bredehoeft, 2002).

Also unfortunately, most of the focus is on water levels and recharge rates, and the question of groundwater pollution is largely secondary. This is in urgent need of correction. Legislation to protect aquifers from pollution has been in place in most of the developed world for two decades now, but it is largely lacking elsewhere. Moreover, aquifers polluted in the heyday of industrial expansion and agricultural intensification in the mid to late twentieth century are now suffering from a legacy that may take many decades to clear. One of the most disconcerting aspects is the discovery that groundwater overdraft may create homespun pollution as in the case of arsenic.

There is a clear argument for more integrated management of surface and subsurface resources. Many problems have been caused by management of one without consideration of the other. However, there is also a need for caution in applying the currently favoured models of Integrated Water Resources Management (IWRM) and the more recent Integrated River Basin Management (IRBM) where surface and subsurface catchments do not coincide. The WHYMAP map clearly shows many cases of non-correspondence, even at the 1:25 million scale, and there are many more localised cases of so-called leaky basins because of this. Rivers can drain water in one direction and the aquifers in another: river basins generally lead to the sea; groundwater basins are defined by rock structures.

There is an even more urgent need for greater integration in the management of transboundary resources. And, indeed, there is a need for more cross-fertilisation and cross-disciplinary collaboration between hydrogeologists and hydrologists. Hydrological processes are not as neatly compartmentalised as scientific disciplines.

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# Groundwater and Health: Meeting Unmet Needs in Sub-Saharan Africa

Segun Adelana, Wilson Fantong, Dessie Nedaw,
and Anthony Duah

**Abstract**

Groundwater plays a vital role in both human life and ecosystem. All over the world, industrial development, agriculture and human existence and health depend on the availability of good quality water in sufficient quantity. In Africa groundwater is a critical resource: Nearly 80% of the continent's population uses groundwater as its main source of drinking water – but in many parts of the region reaching basic water requirements for health is still of concern. This is reflected by the high Human Poverty Index, which is a function of access to adequate and potable water. There is considerable progress towards the Millennium Development Goals (MDGs) in Africa with regard to meeting basic water and sanitation needs; thus, the effects on human health face a downward trend. However, records of health cases relating to consumption of groundwater in some part of Africa calls for increased attention if the MDGs are to be achieved. In this chapter, cases of groundwater quality, particularly drinking water supply, have been reviewed in relation to human health. Case histories are taken mainly from West–Central Africa and East Africa to illustrate the fact that there are unmet needs in health traceable to groundwater quality and inadequacies in water supply.

**Keywords**

Groundwater quality • Fluoride • Nitrate • Health risks • Drinking water • Millennium Development Goals

## Introduction

In Africa groundwater is a critical resource playing a vital role in both human life and ecosystem. The global industrial development, advances in agriculture, human existence and health all depend on the availability of good quality water in sufficient quantity. Looking at the records, regions of the world that have sustainable groundwater balance are shrinking. Four problems dominate groundwater use: depletion due to overdraft; waterlogging and salinization due mostly to inadequate drainage and insufficient conjunctive use; pollution due to agricultural, industrial and other human activities (Shah et al., 2000); and climate variability due to global warming. In regions of the world, especially

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those with high population density, tubewell-irrigated agriculture and insufficient surface water, many consequences of groundwater overdevelopment are becoming increasingly evident (UN-FAO, 2007; Shah et al., 2000).

The most common symptom in such cases is secular decline in water tables. However, groundwater problems in sub-Saharan Africa are not that of overdevelopment (per se) as it is becoming increasingly evident in other developing world. Yet it presents complexity of issues that require technological capacity and hydrogeological information, institutional strengthening to improve management and developmental planning of the groundwater resource. In the absence of these, sustainable use of available groundwater resources in the cause of reducing poverty and enhancing livelihoods (the target of the MDGs) can be difficult to achieve. A recent World Bank report on groundwater in rural development presents “the problem of increasing high rates of waterwell construction failure (due to insufficient yield and/or inadequate quality) in areas of complex and/or unfavourable hydrogeology” (Foster et al., 2000), aside poor construction. This remains untackled and represents a fundamental threat to the well-being of the rural people as they go back to the streams, which are in most cases polluted.

The situation in many parts of Africa, in particular, may be critical and compounded with the high population growth rate and increased urbanization. In addition to water stress and scarcity, excess nitrate concentration due to increased agriculture; fluoride contamination of groundwater in hard rock terrain of western, central and eastern African states; and consequent health effects on humans and livestock are of concern. The approach used in this study combines the results of both field and web-based data to illustrate provenance of fluoride and nitrate in SSA in relation to health implications. Geochemical knowledge from analyses with spatial information on geology and climate is in some places superimposed to give a present-day picture of pollution. The resulting effects are traced to reported cases of illness and recurrent deaths, particularly in children. Providing safe drinking water supply; treatment of domestic and industrial wastewater; and management of solid waste generated in the towns and cities are some of the present and future challenges. The health and socio-economic implications of this situation cannot be over-emphasized. Nevertheless, the strategic role of groundwater is yet to be fully understood by the governments and water policy makers. The management of groundwater resource is still a game of chance in many countries; it has remained a poorly managed resource even in the extensive drought-prone areas of southeastern, eastern and northwestern Africa – especially where the average rainfall is less than 1000 mm/a.

## Groundwater Situation in Sub-Saharan Africa (SSA): Overview of Opportunities and Challenges

Groundwater offers a few but precious opportunities for alleviating the misery of the poor, but it posses many challenges of preserving the resource itself. In SSA, there is some action by way of a response to the growing scarcity of groundwater, but it may be too little, too late, since this is still experimental and there is little approach to economizing on its use. There is a general perception that groundwater resources remain abundant in Africa. While some aquifers are not fully developed for human use, others are over-exploited and almost facing groundwater mining. The question of the quantification of this “hidden” resource and the quality of what is available for domestic use require satisfactory answers. Groundwater is also emerging as a critical issue for cities and towns. At the heart of the urban groundwater problem is population density; cities are getting congested in most parts of SSA. Small towns rapidly develop into cities, while a number of African cities are now growing into megacities. Some of the densely populated large- and medium-sized cities in SSA depend on groundwater. Virtually, in all the cases the rate of expansion does not match planning for water and basic sanitation services. In addition to this is that cities just do not have a large enough recharge area to support or meet the water supply needs of their inhabitants on a sustainable basis. These cities may face acute water shortages in a medium term to long term.

Urban industrialization is also a major contributor to urban groundwater problems. Although these are interwoven, industries are sited in urban centres where there is sufficient labour. On the other hand, rural dwellers are on a constant move to cities in search of white-collar jobs, thus compounding the problem of water supply. Industries are also known to generate lots of wastes that contribute to surface and groundwater pollution. Effluent discharge from industries is not properly monitored in many industrial centres in SSA. Legislations and its enforcements are necessary to reduce the risk that comes back to humans through these activities.

Another challenging situation in SSA is over-utilization of coastal aquifers. Several of the nations' capital cities are located along the coast, most of which are equally industrial centres, attracting rural dwellers. Water supply services to meet the demand in coastal cities are complex: groundwater mixing and saline water intrusion are challenging issues for the future. Groundwater overdraft has many negative consequences. The most far-reaching impact of groundwater depletion and water quality deterioration is on the health of large sections of rural populations that depend directly on wells as their only source of drinking water supply.

Generally, most of the rural communities have traditionally relied mainly for their water supply needs on sources which range from dug wells, ponds, dugouts, dam impoundments, streams, rivers to rainwater harvesting from roofs. Most of these sources particularly those based on surface water resources are polluted and are the main sources of water-borne diseases so common in the rural areas. Diseases and poverty are hence endemic in many rural communities and urban squatter camps.

In Cameroon, some 2 million city dwellers lack safe drinking water and adequate sanitation, resulting in outbreaks of cholera. Children living in urban poverty are especially vulnerable to illness, violence and exploitation (UNICEF, 2007). Infant and under-5 mortality rates in 2005 were actually higher than their 1990 levels. In Ethiopia, the under-5 mortality rate is 123 per 1000 (WASH, 2008). Sanitation and hygiene-related diseases are among the most common deadly diseases in Ethiopia. In Nigeria, only 60% of households have access to improved drinking water sources while access to adequate sanitation facilities remains low.

Presently in Ghana about 52% of the rural inhabitants have access to potable water mainly from groundwater sources (Gyau-Boake et al., 2008). To improve the standard of living and boost economic activities in the rural areas, the government has drawn up a policy of supplying most of the rural communities with potable water. The task ahead of the government of Ghana is that of achieving its goal of covering about 85% of the rural communities with potable water by 2015. This is planned to be achieved by sinking more boreholes. This is because groundwater is not only feasible but also the most economic source of potable water due to the dispersed nature of the rural settlements. Therefore, it is imperative to see the role of groundwater in rural and urban supplies and the pace towards MDGs for water and sanitation.

## Sustainable Water Resource Management and the Millennium Development Goals

Going by the UN definitions, The Millennium Development Goal 7 on Environmental Sustainability is to halve the proportion of people living without access to an improved source of drinking water and basic sanitation between 1990 and 2015 (UN Millennium Project Task Force on Water and Sanitation, 2005). The progress so far may not be at the pace desired, and the situation with water and sanitation in SSA may even require a greater attention. Tables 1 and 2, respectively, show the position of SSA in the target for safe drinking water and basic sanitation. From the tables the picture is clear on the progress as to meeting the Millennium Development Goal Water and Sanitation Target and as to what increases are needed in developing regions? Although the world needs to accelerate the provision of safe drinking water and basic sanitation services by 58% to meet the MDG target, SSA is lagging furthest behind (as indicated in Table 2).

According to UNICEF data on emergency of simple needs, 42% of people living in SSA are drinking unsafe water. Based on UN projections, SSA will need to quadruple the additional number of people served with basic sanitation (UNICEF, 2007). Of the 1.9 million children under 5 dying every year of diarrhoeal diseases, some 769,000 are in sub-Saharan Africa (UNICEF/UN Data, 2007). Table 3 shows children health statistics in East and West Africa (data curled and compiled from UNICEF database). Therefore, achieving the Millennium Development Goals (MDGs) in SSA anchors significantly on increasing rural water supply coverage and improving sanitation practices (which constitute threat to groundwater quality). This has a two-faced challenge: increased dependence on groundwater and protection of aquifers to avoid further water quality degradation.

**Table 1** Meeting the MDGs – progress towards the drinking water target (JMP 2008)

| | Drinking water coverage (percentage of population) | | | | Annual increase in people served 1990–2002: (thousands) | Annual increase needed to reach the target 2002–2015: (thousands)[b] |
|---|---|---|---|---|---|---|
| | 1990 | 2006 | 2015[a] (projected) | MDG target | | |
| Northern Africa | 88 | 92 | 92 | 94 | 2383 | 3009 |
| Sub-Saharan Africa | 49 | 58 | 65 | 75 | 12,524 | 21,485 |
| Latin America and the Caribbean | 84 | 92 | 89 | 92 | 9135 | 7891 |
| Eastern Asia | 68 | 88 | 78 | 84 | 16,086 | 15,889 |
| South Asia | 74 | 87 | 82 | 87 | 34,350 | 23,549 |
| Southeast Asia | 73 | 86 | 82 | 87 | 8208 | 9663 |
| Western Asia | 86 | 90 | 90 | 93 | 4034 | 4576 |
| Oceania | 51 | 50 | 67 | 76 | 93 | 283 |
| **World** | **77** | **87** | **84** | **89** | **90,836** | **96,568** |

[a] Projected coverage in 2015 is extrapolated from rates of progress between 1990 and 2002

[b] The increase needed to reach the MDG water and sanitation target is based on the MDG target and the unserved population in 2002, factoring in projected population growth between 2002 and 2015. Note that the individual regions do not add up to the total due to rounding.

**Table 2** Meeting the MDGs – progress towards the sanitation target (JMP 2008)

| | Sanitation coverage (percentage of population) | | | | Annual increase in people served 1990–2002: (thousands) | Annual increase needed to reach the target 2002–2015: (thousands) |
|---|---|---|---|---|---|---|
| | 1990 | 2006 | 2015 (projected) | MDG target | | |
| Northern Africa | 62 | 76 | 82 | 81 | 2632 | 3341 |
| Sub-Saharan Africa | 26 | 31 | 40 | 63 | 7011 | 26,727 |
| Latin America and the Caribbean | 68 | 79 | 82 | 84 | 8053 | 10,424 |
| Eastern Asia | 24 | 65 | 68 | 65 | 27,613 | 22,700 |
| South Asia | 20 | 33 | 55 | 61 | 25,875 | 41,645 |
| Southeast Asia | 48 | 67 | 75 | 75 | 9778 | 10,511 |
| Western Asia | 79 | 84 | 79 | 90 | 3151 | 5409 |
| Oceania | 58 | 52 | 52 | 76 | 80 | 289 |
| **World** | **54** | **62** | **68** | **777** | **87,164** | **137,796** |

A very large proportion of Africa's population live in communities for which groundwater is likely to be the only realistic option for improved water supply. Groundwater will have to be given higher priority and greater investment to achieving the UN Millennium Development Goals in SSA. Critical issues for future groundwater development to achieving improved rural water supplies in SSA have been highlighted in Foster et al. (2008). Groundwater management issues in SSA with a perspective on Integrated Water Resources Management are presented in the southern Africa example (Braune and Xu, 2008; Braune et al., 2008). The capacity-building initiatives of Cap-Net/BGR in part of SSA are yielding favourable results. What remains unanswered are the future health and well-being of African people and the socio-economic implications of not meeting the MDGs on water and sanitation. There is an increasing need for coordination and integrating local development efforts with investments from the international community/organizations.

The Joint Monitoring report (WHO–UNICEF) recommends five key complementary actions to reach the water and sanitation MDGs (over the International Decade for Action on Water for Life). Crucial among these are significantly increasing access to safe drinking water and meeting basic sanitation demand. Failure to meet these simple needs may cost many

**Table 3** Children Health Statistics in West and East Africa (UNICEF Data 2007)

| Basic indicators | Countries | | | | |
|---|---|---|---|---|---|
| | Cameroon | Ethiopia | Ghana | Nigeria | Uganda |
| Under-5 mortality rank | 18 | 27 | 30 | 8 | 21 |
| Under-5 mortality rate (1990) | 139 | 204 | 120 | 230 | 175 |
| Under-5 mortality rate (2007) | 148 | 119 | 115 | 189 | 130 |
| Infant mortality rate (under 1), 1990 | 85 | 122 | 76 | 120 | 106 |
| Infant mortality rate (under 1), 2007 | 87 | 75 | 73 | 97 | 82 |
| Total population (thousands), 2007 | 18,549 | 83,099 | 23,479 | 148,093 | 30,884 |
| Annual no. of births (thousands), 2007 | 649 | 3201 | 703 | 5959 | 1445 |
| Annual no. of under-5 deaths (thousands), 2007 | 96 | 381 | 81 | 1126 | 188 |
| % of population using improved drinking water sources, 2006, total | 70 | 42 | 80 | 47 | 64 |
| % of population using improved drinking water sources, 2006, urban | 88 | 96 | 90 | 65 | 90 |
| % of population using improved drinking water sources, 2006, rural | 47 | 31 | 71 | 30 | 60 |
| % of population using adequate sanitation facilities, 2006, total | 51 | 11 | 10 | 30 | 33 |
| % of population using adequate sanitation facilities, 2006, urban | 58 | 27 | 15 | 35 | 29 |
| % of population using adequate sanitation facilities, 2006, rural | 42 | 8 | 6 | 25 | 34 |

more children their lives (WHO, 2005). In SSA, adequate water and sanitation infrastructure is the only means possible of supporting socially, economically and environmentally sustainable development of urban areas.

There are potentially powerful indirect demand management strategies that are not even part of the academic discussion in the developing world. These offer opportunity for new approaches, adaptation of proven management schemes elsewhere in the world and the need for closer scrutiny. There is also scope and need for more orderly development of groundwater for irrigation, especially in West Africa and East Africa where potential for groundwater development still exists.

A major barrier that prevents transition from the groundwater development to management mode is lack of information. Many countries of sub-Saharan Africa do not have any idea of how much groundwater is present and who withdraws how much groundwater and where. Indeed, even in countries where groundwater is important in all uses and where there is some knowledge about water resources, systematic monitoring of groundwater occurrence and abstraction is still lacking.

## Cases of Aquifer Pollution and Health Effects

The conditions under which groundwater is found and the quantity and quality of groundwater reserves are closely related to geologic setting in the different parts of Africa. There are quality implications on the water flowing through or hosted within these rocks. For example, recent investigation of fluoride prevalence in Africa (IGRAC, 2009) is shown in Fig. 1. In SSA, aquifer pollution – from both point and non-point sources – is becoming extensive. Although there are maps and available data on aquifer distribution, the extent of pollution studies is still localized, and a broader regional assessment is scanty. However, there is a reasonable record of publications on groundwater pollution based on countries or basins or even related to specific aquifers.

Most of the exploited groundwater is generally fit for consumption because the dissolved minerals in water from shallow wells, particularly in the sandy coastal aquifers and weathered basement rocks of West Africa, are quite low. Groundwater from deeper aquifers occurs in Ethiopia and other parts of East

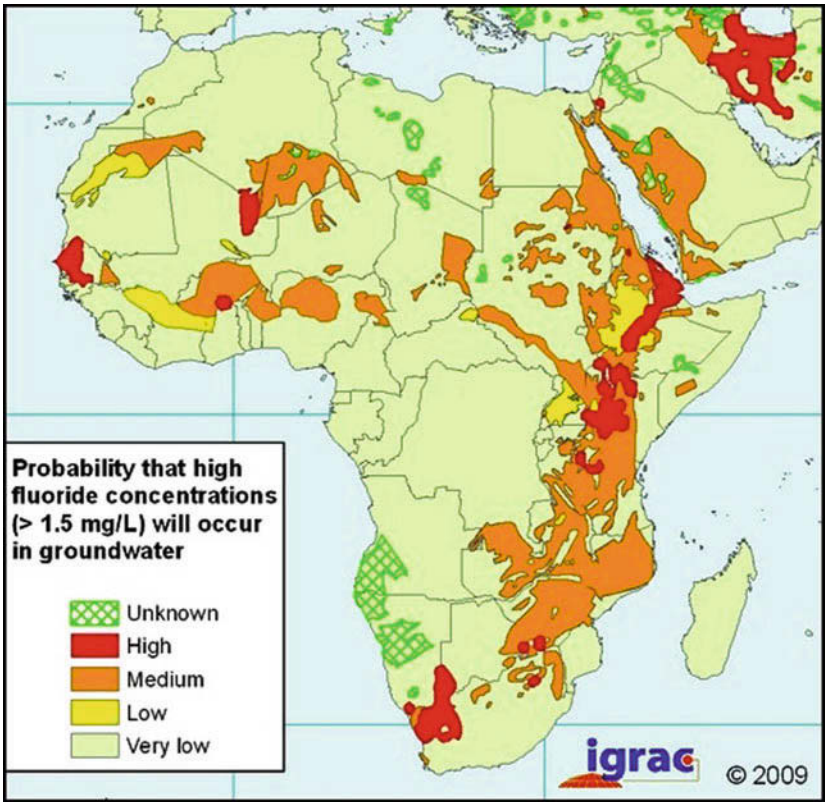

**Fig. 1** Fluoride concentration in groundwater in Africa (IGRAC 2009). In 2009 IGRAC updated the probability map of Fluoride occurrence in Africa with more recent findings. For more information see Vasak et al. (2010)

Africa and may have a high content of dissolved salts. In moist, tropical countries groundwater hosted in fractured, Precambrian rocks generally contains low dissolved minerals, whereas in the volcanic areas (for example, of East Africa) groundwater may have so high a content of fluorine as to make it unfit for human consumption.

Most of the accessible published information in Ethiopia is for water quality within the Rift Valley (Kloos and Haimanot, 1999; Tamene, 2006; Tekle-Haimanot et al., 2006; DFD, 2008). From this, it is evident that groundwater in the Rift zone is influenced by geothermal waters with abnormally high concentrations of fluoride and/or total dissolved salts. Fluoride is therefore a recognized major problem (Fig. 2), especially for the communities living within the Rift valley basin (Ethiopia). From 10 million people living in Ethiopia Rift zone, about 8.5 million people (12% of the country's population) are exposed to high fluoride contamination (Tamene, 2006). In Ethiopian Rift Valley waters, fluoride varies from 0.5 to 264 mg/l (up to 26 mg/l in drinking water sources). Over 40% of deep and shallow wells and springs in the rift valley have fluoride levels above the optimal (WHO, 2004) level of 1.5 mg/l. More than 80% of the children in the rift valley have developed varying degrees of dental fluorosis, while crippling skeletal fluorosis are common to old people (Tamene, 2006). The worst cases of skeletal fluorosis are recorded at Wonji (Ethiopia) and attempts to defluoridate the water are ongoing. Dental fluorosis is also recognized in some highland communities (Kloos and Haimanot, 1999) where the water is abstracted from volcanic rocks.

Studies indicate that the volcanic rocks of East Africa are found to be richer in fluoride than analogous rocks in other parts of the world (Tekle-Haimanot et al., 2006; Kloos and Haimanot, 1999). The sources for anomalous amounts of fluoride and sodium in surface and ground water have been traced to acidic rocks such as pumice deposits in the East African Rift Valley in Ethiopia. On the other hand, the high fluoride concentrations in the ground waters of the rift valley are believed to be enhanced due to the high $CO_2$ pressure, hydrothermal heating, and low calcium and low salinity fluids while high fluoride, salinity and alkalinity in closed-basin lakes result from

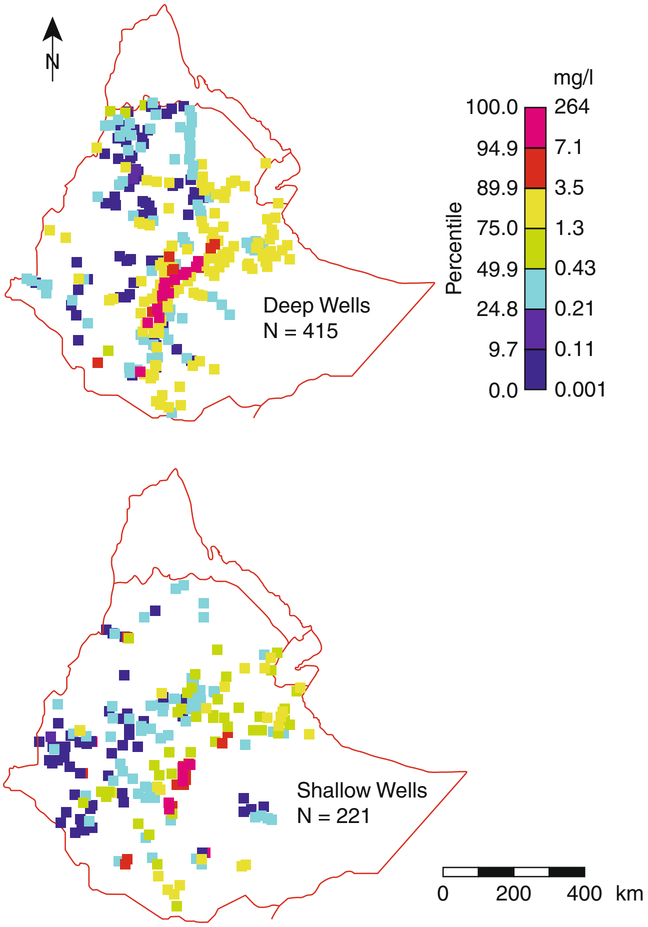

**Fig. 2** Fluoride levels in deep and shallow wells in Ethiopia (Tekle-Haimanot et al., 2006)

evaporative concentration. Observed increased salinity in groundwater from sedimentary aquifers in the south, southeast and northeastern parts of the country arises from the dissolution of evaporite minerals.

Nitrate and other pollution indicators could also be high in Ethiopian drinking water. UN (1989) reported that nitrate concentrations are high in groundwater from several urban areas (especially around Dire Dawa and Addis Ababa) as a result largely of leaking effluent from septic tanks. Nitrate concentrations are likely to be worst in urban areas where the water tables are reasonably close to the ground surface (i.e. within 10–15 m). Nitrate concentrations may also be increased in some of the saline groundwaters affected by evaporation.

In Cameroon, the various aquiferous formations are represented in a schematic map (Fig. 3). The cases of groundwater-related problems associated with each of these aquifers are presented in Table 4. The sources of contamination and the reported associated health problems are also indicated.

The 500,000 inhabitants of Mayo Tsanaga River Basin (Cameroon) are vulnerable to a “silent” fluorosis from groundwater consumption. In the study to trace the provenance of fluoride and to estimate optimal dose of fluoride in the Mayo Tsanaga River Basin a fluoride concentration range in groundwater was 0.19–15.2 mg/l. Severe clinical evidence of fluorosis was identified in children living in Meri village (Cameroon), through daily record in a local hospital (Fantong et al., 2009). Sample with fluoride content of less than 1.5 mg/l shows Ca-$HCO_3$ signatures, while those with fluoride greater than 1.5 mg/l shows a tendency towards Na-$HCO_3$ type. It was established that pegmatitic granites were the dominant provenance of the fluoride, which dissolved in the groundwater as a function of alkaline medium, long residence time, sodium exchange for calcium, and anion (fluoride and

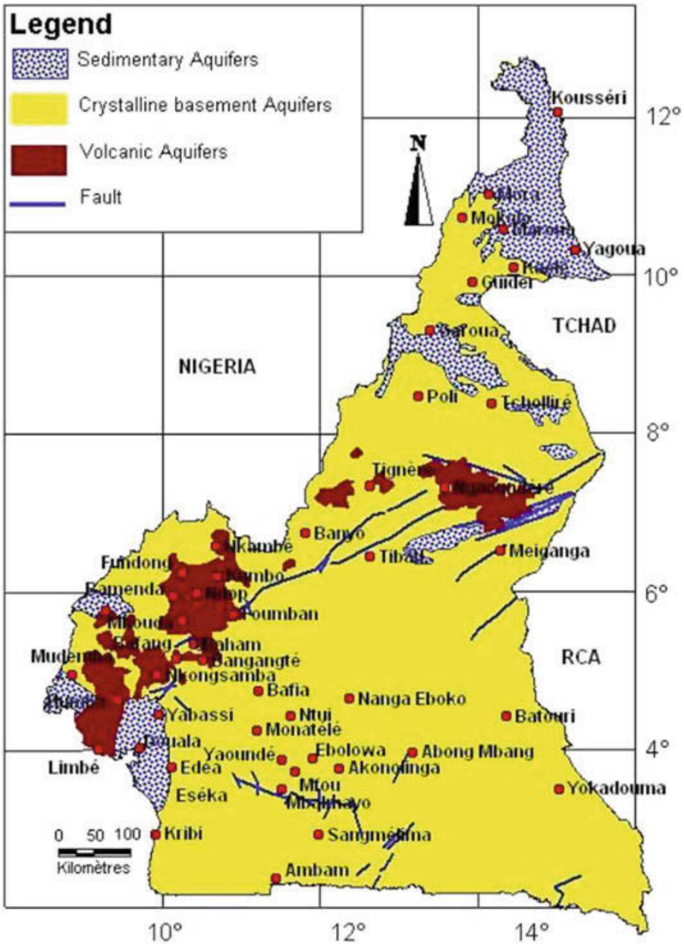

**Fig. 3** Schematic map of the main aquiferous formations in Cameroon (modified from Mafany et al., 2006)

OH) exchange as the groundwater interacts with fluorapatite and micas in the granites. By the influence of high atmospheric temperature which catalyses high consumption rate of the groundwater, an optimal fluoride dose of 0.7 mg/l was estimated and is advocated for drinking water in the Mayo area. For the reason that the estimated optimal fluoride dose is about 50% less than the 1.5 mg/l set by the WHO is an indicator that SSA countries have another challenge of establishing and implementing national/local drinking water standards.

In Ghana, concentrations of fluoride in excess of 1.5 mg/l (up to 3.8 mg/l) have been observed in Bongo District (Upper East Region, Fig. 4) in close association with granitic rock types, called Bongo Granite (Smedley et al., 1995). According to the British Geological Survey reports, the occurrence of dental fluorosis is common in these areas. Groundwaters in granitic rocks of the southwest plateau are considered to be less at risk because of higher rainfall and its diluting effect on groundwater compositions. Marked variations in fluoride concentration with depth were observed in groundwaters from the problem areas of Bolgatanga (e.g. the Bongo Granite, Fig. 4). Shallow groundwaters from dug wells had significantly lower concentrations than tubewell waters as a result of dilution by recent recharge.

Hydrochemical composition of groundwater in the Offin Basin has shown that iron (Fe) poses major aesthetic problems as approximately 46% of the boreholes have iron concentration higher than the WHO (2004) guideline limit of 0.3 mg/l, which has sometimes led to borehole rejection (Kortatsi et al., 2007). From this work a major physiological problem is also posed in the basin by arsenic, as approximately 21%

**Table 4** Groundwater-related problems and the reported associated health effects in Cameroon

| Aquifer location | Reported groundwater contamination | Source of contamination | Reported associated health problems | Reference |
|---|---|---|---|---|
| **Chad basin** | Nitrate pollution | Anthropogenic[a] | Diarrhoea | Fantong et al. (2009), Ngounou-Ngatcha et al. (2001) |
| | Fluoride contamination | Lithogenic | Fluorosis | Fantong et al. (2009, 2010) |
| **Garoua basin** | Fluoride contamination | Not documented | Not documented | Mafany et al. (2006) |
| **Mamfe basin** | Saline groundwater | Evaporites | Not documented | Eseme et al. (2006) |
| **Rio del Rey basin** | Saline groundwater | Evaporites and seawater | Diarrhoea and unpleasant taste | Fantong et al. (2001) |
| | Iron contamination | Lithogenic | Cholera and bad flavour | Ako et al. (2008) |
| | Nitrate pollution | Anthropogenic[a] | Gastrointestinal problems | Fantong (1999) |
| **Douala basin** | Saline groundwater | Seawater intrusion | Unpleasant taste | UNEP/DEWA[b] |
| | Nitrate and microbial pollution | Anthropogenic[a] | Diarrhoea, cholera | Ndjama et al. (2008) |
| | Aquifer material (soil) pollution by trace elements | Anthropogenic[a] and lithogenic | Not documented | Asaah et al. (2006) |
| **Crystalline aquifers (in Yaounde)** | Microbiological pollution | Anthropogenic[a] from hospitals | Not documented | Kuitcha et al. (2008) |
| **Volcanic aquifers** | Fluoride contamination | Lithogenic | Not documented | Tanyileke et al. (1996) |

[a] Point source

[b] UNEP/DEWA: Africa Environment Outlook (www.unep.org/dewa/africa/publications/aeo-1/165.htm)

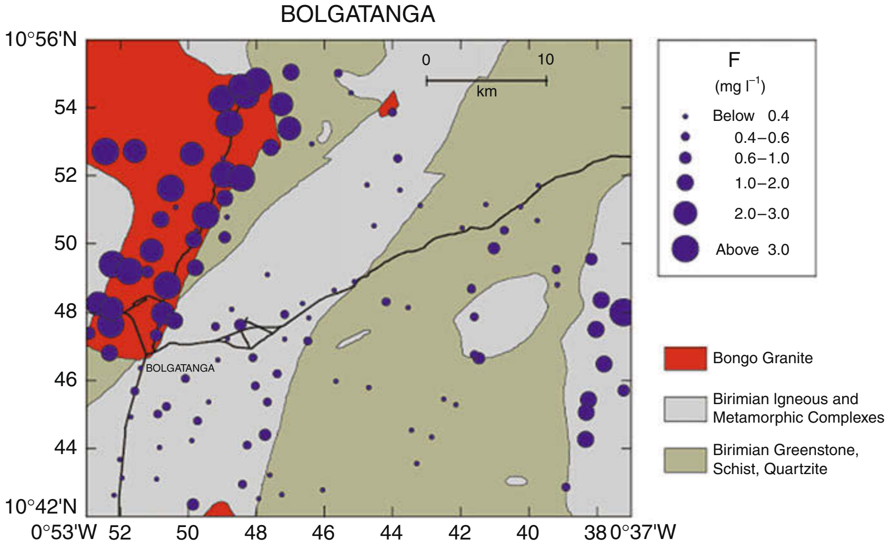

**Fig. 4** Distribution of fluoride in groundwater of the Bolgatanga area superimposed on geological map, Upper East Region (northern Ghana). Data and Information Source: BGS, 1999

**Table 5** Summary of potential groundwater quality problems in Ghana

| Determinant | Potential problem | Geology | Location |
|---|---|---|---|
| Iron (Fe) | Excess, often significant | All aquifers | Many locations |
| Manganese (Mn) | Excess | All aquifers | Several locations |
| Fluoride (F) | Excess (up to 4 mg/l) | Granites and some Birimian rocks | Upper Regions |
| Iodine (I) | Deficiency (less than 0.005 mg/l) | Birimian rocks, granites, ?Voltaian | Northern Ghana (especially Upper Regions) |
| Arsenic (As) | Excess (>0.01 mg/l) | Birimian | Especially southwest Ghana (gold belt) |

of the boreholes sampled have arsenic concentration exceeding the maximum provisional guideline limits of 10 μg/l. Other potential groundwater quality problems in Ghana are summarized in Table 5 (BGS, 1999).

In Nigeria, the occurrence of dental fluorosis has been reported in some northern communities resulting from drinking water (Wongdem et al., 2000; Apata, 2004; Fawell et al., 2006). A total of 475 people aged 5 and over, who were either born in Langtang town (Nigeria) or had lived there for a minimum of 5 years, were examined for mottling teeth. The results revealed there was a 26% prevalence rate of enamel fluorosis in the Langtang area, with 21% cases classified as mild and 5.5% as severe (Wongdem et al., 2000). The highest prevalence was reported to be among teenagers, particularly 10–19 years old. A follow-up study to determine the fluoride concentration in Langtang town found that levels ranged between 0.5 and 4 mg/l in streams and groundwater (Wongdem et al., 2001).

**Table 6** Nitrate distribution in groundwater from various geological formations in Nigeria (Adelana, 2006)

| Groundwater region | Hydrostratigraphic units | Lithology | Maximum $NO_3$ level (mg/l) | No. of samples | % over 45 mg/l |
|---|---|---|---|---|---|
| Basement-fluvio-volcanics | Younger granite aquifuge | Weathered basalts, buried alluvium regolith | 300 | 120 | 13 |
| | Granite, metamorphic aquifuge | Fractured granite, gneiss, schists, metasediments | 225.4 | 288 | 17 |
| Sokoto basin | Kalambaina aquifer | Fine-coarse sand “limestone”, clay | 97.1 | 52 | 33 |
| | Taloka/Wurno aquifer | Coarse sand, limestone | 39.1 | 74 | 18 |
| Chad basin | Upper aquifer | Silts, sands, gravels, clays | 134.4 | 360 | 29 |
| | Lower aquifer | Sands, fine-coarse sands, clay intercalations | 112 | 12 | 20 |
| Nupe basin | Nupe sandstone aquifer | Fine-coarse sands | 88 | 69 | < 1 |
| Yola basin | Alluvial aquifer | Grits, sandstone, clay | 72 | 12 | 16 |
| | Bima sandstone aquifer | Sandstone, micaceous shale–mudstone | 150 | 18 | 10 |
| Anambra-Benin basin | Ajali Sandstone aquifer | Coarse/medium sands, clay interbeds | 135 | 65 | 27.5 |
| | Enugu shales | | 472 | 14 | 25 |
| Calabar Flank basin | Coastal plain sand aquifer | Red sands, thin clay interbeds | 1, 101 | 67 | 80 |
| | Eastern Delta | Sands, clay interbeds | 3, 869 | 120 | 95 |
| Lagos-Osse basin | Alluvial, coastal sand aquifer | Sands, gravels, silt, clay | 284.7 | 88 | 52 |
| | Ilaro/Ewekoro aquifer | Clay sands, sand silt, limestone beds | 107.8 | 112 | 25 |

Recent studies (Akpata et al., 2009) investigated fluoride levels in drinking water sources from 109 randomly selected local government areas (LGAs) in 6 Nigerian geopolitical zones. From the results, maps showing LGAs with fluoride concentrations exceeding 0.3 mg/l were drawn. About 21% of the LGAs in the country had fluoride concentration of 0.31–0.60 mg/l in their drinking water sources; the North Central geopolitical zone had the highest proportion of LGAs (45%) with this fluoride level, followed by the North West geopolitical zones (35%). Other health problems resulting from drinking water are related to nitrate (Adelana and Olasehinde, 2003; Adelana, 2004), heavy metals and microbial coliform (Aremu et al., 2002).

The average level of nitrate in groundwater in Nigeria has increased in the last 30 years due to increased agricultural activities and the increased use of land to dispose of waste indiscriminately. This was based on the analyses of groundwater samples from over 2200 wells, mostly supplying drinking water to homes or for domestic use. The results of the survey show that 33% of wells produced water with a nitrate concentration, that is, above the WHO guide limit of 45 mg $NO_3$/l (Adelana, 2006). Distribution according to hydrogeological units is illustrated in Table 6. The highest risk is for infants <3 months old who are bottlefed using groundwater with >50 mg/l $NO_3$-N, and confounding factors (such as lack of vitamin C, gastrointestinal infections and cancer risks) are evidently discussed in Adelana (2005).

Possible negative health effects of increased nitrate concentrations are methaemoglobinaemia, especially for infants; in which the body development, nervous and heart systems of children can be affected. The presence of the nutrients nitrogen (in the form of nitrate and ammonia) and phosphorus in water is generally considered to be a manifestation of pollution. In the case of groundwater, pollution is more difficult to trace and the effects are not as obvious. Due to lack of clinical data it was difficult to link the infant mortality rate with nitrate ingestion through bottlefeeding, as was done in the southern part of Africa (Colvin, 1999).

## Conclusions

In this chapter, groundwater resources in sub-Saharan Africa have been reviewed in terms of quality in the bid towards Millennium Development Goals. This has been driven by the targets for drinking water and sanitation, which were the prime water-related outcome of the World Summit on Sustainable Development in Johannesburg in 2002. The status of sub-Saharan Africa (SSA) as compared to other developing world in the journey towards the target is of concern. Many issues still need to be addressed in the light of experiences in rural water supply across the countries. The cases discussed in this chapter demonstrate evidence of health problems traceable to natural and anthropogenic sources. The ingestion of high fluoride and nitrate through drinking water illustrated the silent epidemics that are not yet fully addressed. Aside geologic factors, there is a list of human activities in the region that contaminate water sources, i.e., agriculture, sanitation practices, industry, mining, military and burial sites, waste disposal and traffic.

Groundwater offers precious opportunities for alleviating the misery of the poor, but it possesses many and daunting challenges for preserving the resource itself. In SSA, there is some action by way of a response to the growing scarcity of groundwater, but it is too little, too late, still experimental and there is precious little on approaches to economizing on its use. Groundwater interventions in water supply often tend to be too local and restricted to the rural areas. Like surface water, groundwater resources too need to be planned and managed for maximum basin-level efficiency.

Understanding health aspects of groundwater is crucial to developing management strategies and opens the door to potential management actions that may be taken to protect drinking water sources. It is a useful approach to analyse hazards to groundwater quality, characterizing and/or assessing the risk these may cause for a specific supply is crucial and calls for comprehensive research. Setting priorities in addressing these may be the beginning of a comprehensive water safety plan for rural and urban communities in sub-Saharan Africa. Propagation of laws and regulations for the control of risks associated with these activities is an issue in many countries in SSA. The water laws and regulations are not weak in themselves, where they exist, but their implementation has defects. The political will needed to implement these regulations must be geared up, primarily at the local level involving the people, local governments and non-governmental organizations but with responsive participation and contributions of the international community. There is a long-term profit in being able to set and enforce the laws governing water and environmental pollution in the various countries of Africa. This will, obviously, set the stage for the protection of groundwater in specific regions averting future health problems.

There are a number of strategies which have proven results of success in other parts of the world that may be adopted in some of the countries in SSA. The countermeasures to control water pollution may include (i) proper siting and improving well construction in rural areas; (ii) increasing the consciousness of water resources protection; (iii) integrated management of water resources; (iv) adopting effective measures and establishing water-saving approaches to avoid overdraft and industrial waste reduction; and (v) perfecting/implementing the existing laws and regulations on water quality.

There are potentially powerful indirect demand management strategies that are not even part of the academic discussion in the developing world. These offer opportunity for new approaches, adaptation of proven management schemes elsewhere in the world and the need for closer scrutiny. There is also scope and need for more orderly development of groundwater for irrigation, especially in West Africa and East Africa where potential for groundwater development still exists.

A major barrier that prevents transition from the groundwater development to management mode is lack of information. Many countries of sub-Saharan Africa do not have any idea of how much groundwater is present and who withdraws how much groundwater and where. Indeed, even in countries where groundwater is important in all uses and where there is some knowledge about water resources, systematic monitoring of groundwater occurrence and abstraction is still lacking.

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# Karst, Uranium, Gold and Water – Lessons from South Africa for Reconciling Mining Activities and Sustainable Water Use in Semi-arid Karst Areas: A Case Study

Frank Winde

**Abstract**

Despite the fact that much of the water stored in dams and reservoirs is lost to the atmosphere due to prevailing semi-arid conditions, South Africa traditionally relies mainly on surface water. Owing to an ever increasing demand that approaches the limits of economically exploitable surface water, the focus increasingly shifts towards groundwater as a long neglected resource. In this context, dolomitic karst aquifers that store large volumes of water protected from evaporation in vast underground cavities are of particular importance. This even more so as some of these aquifers are located in highly industrialised and densely populated areas such as the Gauteng Province, where water demand by far exceeds local supply and necessitates the expensive import of water from catchments as far as Lesotho. However, owing to impacts related to the century-old, deep-level gold mining that initiated South Africa's economic development, many of the karst aquifers are currently not usable. Using the Far West Rand goldfield as an example, the extent, type and magnitude of mining-related impacts on dolomitic karst aquifers are analysed. This includes impacts on the geohydrological conditions in the area as well as water availability and ground stability associated with the large-scale dewatering of dolomitic aquifers that overly mine workings. Of particular concern is the mining-related contamination of groundwater and surface water with uranium which accompanies gold in most of the mined ore bodies. Finally, possible scenarios for water-related impacts of future mine closure are outlined and associated research needs identified.

**Keywords**

Karst • Dolomite • Aquifer • Deep-level gold mining • Dewatering • Uranium • Contamination • Groundwater • Health effects • Mine closure • Far West Rand • South Africa

## Introduction

Located in the same type of subtropical high-pressure zone that renders much of Africa north of the equator a desert, South Africa (SA) is a generally water scarce country with many areas receiving much less rainfall than potentially lost to the atmosphere.

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Despite the chronic water shortage, mining of diamonds and later gold allowed SA during the past century to reach levels of industrialisation comparable to many Western economies. This was accompanied by one of the largest urban agglomerations in Africa developing around a former mining camp now known as Johannesburg.

From the early days of gold mining in the Witwatersrand, access to sufficient water proved to be one of the most limiting factors for economic growth and development. Acute water shortages in the rapidly growing mining town of Johannesburg were at the time overcome through importing groundwater from a nearby karst aquifer, known as the Zuurbekom dolomite compartment.

However, the use of groundwater was soon to become an exception, increasingly replaced by schemes relying on storing river water in large dams. Apart from water for the expanding mining industry and the accompanying urbanisation, in true tradition of the ruling Boers (farmers), much of the water was allocated for irrigation, which to this date continues to remain the single largest water use accounting for over 60% of the total water consumption in SA (DWAF, 2004). In many instances, large-scale governmental projects such as the building of the Vaal Dam or the Vaal-Hartz irrigation scheme during the 1930s were also aimed at fighting unemployment amongst the often unskilled, rural Afrikaner (van Vuuren, 2008).

Although much of the water in the often shallow and large dams is lost to evaporation, surface water schemes soon dominated in SA. Since 1991 this also includes the world's largest transboundary water transfer system known as Lesotho Highland Water Project (LHWP) of which the second phase was recently approved by Cabinet (Institute for Future Research, 2009). The LHWP augments the vastly overstretched resources especially in Gauteng as economic heartland of South Africa where about one-third of the country's gross domestic product is generated. With approximately one-quarter of all South Africans concentrated in the country's smallest province, Gauteng currently needs to import 88% of its water.

Today SA draws the vast majority of its water from rivers and dams contrasting with an almost inverse relation worldwide where most of the drinking water originates from groundwater. With some 320 major dams and associated infrastructure in the form of canals, tunnels and pipelines capturing approximately two-thirds of the total mean annual runoff, SA is now approaching the limits of economically affordable surface water exploitation (DWAF, 2004).

Apart from increasing costs for maintaining and replacing the vast and aging infrastructure, this is also due to a lack of newly exploitable surface water resources. Large-scale water theft in the form of illegal (unauthorised) water abstraction for irrigation further adds to the looming threat of water shortages. As a consequence, the focus shifted to groundwater as a somewhat neglected and partly underutilised resource (DWAF, 2004).

Furthermore, many supply schemes in industrialised and densely populated areas are affected by increasing pollution frequently impacting on vulnerable surface waters more directly and rapidly than on better protected groundwater resources. A major source of microbiological contamination and associated spread of diseases is the uncontrolled growth of informal settlements on the fringes of urban areas frequently lacking even basic sanitation infrastructure. In much of the Witwatersrand Basin as the most densely populated region of SA, this is exacerbated by additional pollution from gold mining, even though many of the mines are now closed.

Having been the economic backbone of SA for more than a century, the revenue-generating gold mines often enjoyed preferential treatment in the past not only in terms of generous water allocation by government but also regarding the toleration of pollution through lack of political will to enforce existing legislation protecting the environment. This situation changed since the establishment of a democratic, non-racial political system in the early 1990s with an increasingly better informed and environmentally conscious society placing political pressure on mines and authorities to implement the advanced environmental legislation introduced since 1994. This is meanwhile met with pro-active responses especially from larger, internationally operating mining houses which, despite a still largely lacking law enforcement, take steps to minimise environmental impacts and thus improve the corporate image.

However, owing to historical and largely unmitigated impacts over more than a century, the challenges of addressing mining-related water problems are varied, complex and often large in scale and magnitude. Recent examples, much publicised in the news media, illustrate that not only operational mines but also abandoned and closed mines may pose a significant pollution threat. Highly contaminated mine water overflowing from flooded (mined-out) underground voids currently pollutes a number of streams on the Witwatersrand with toxic heavy metals and radionuclides amongst other. With all mines ultimately approaching closure in the medium- to long term (approximately 5–40 years from now), decanting mine water may potentially affect a much wider area and many more water users in the densely populated goldfields on the Witwatersrand.

With SA gradually approaching the limits of its surface water-based supply system, the focus of water management recently shifted towards groundwater as an often neglected and underutilised resource.

In this chapter, the emphasis is placed on dolomitic karst aquifers near Johannesburg where some of SA's largest groundwater resources are found. Using historical examples, deliberate and inadvertent impacts of deep-level gold and uranium mining on water availability and water quality will be explored.

Since karst aquifers worldwide constitute the single most important water source by providing over half of all water used globally, lessons from this case study may be of use elsewhere. This is particularly true since mining, especially in developing economies, continues to remain a major source of revenue generation and employment while having considerable potential to adversely affect natural water resources. The focus is specifically on impacts associated with the mining and production of U which currently experiences a global renaissance (Creamer, 2007).

## Dolomitic Groundwater and Mining: A Case Study from the Far West Rand

The Far West Rand (FWR) goldfield (also known as Carletonville goldfield or West Wits Line) was established in the late 1930s when the Ventersdorp Gold Mine as the first mine in South Africa employed a newly developed cementation process that allowed to sink shafts through water-bearing dolomite. This was followed by the establishment of the Blyvooruitzicht Gold Mine further downstream of the Wonderfonteinspruit, which as main drainage channel of the area connects the newly established FWR with the upstream (non-dolomitic) West Rand where mining commenced half a century earlier. Interrupted by the Second World War, the FWR expanded rapidly during the 1950s to become the then richest gold mining area in South Africa and indeed worldwide.

The Wonderfonteinspruit (WFS), meaning 'stream of miraculous springs' in Afrikaans, derives its name from a succession of karst springs dotted along its nearly 100-km-long course starting about 20 km west of Johannesburg south of the continental divide that separates the catchments of the Indian and the Atlantic Oceans. Before joining the Mooi River as a tributary to South Africa's second largest stream, the Vaal River, the WFS drains an area of approximately 1600 km$^2$. Much of the catchment is underlain by highly weathered dolomite deposited some 2.4 billion years ago which is now one of the most extensive karst aquifer system in SA. Weathering mainly affected the upper 50–100 m of the up to 1500-m-thick dolomite forming a 'cavernous zone' that used to store more water than the Vaal Dam as major reservoir for the metropolitan area of Gauteng (Swart et al., 2003a).

The extent to which the dolomites in the WFS area are karstified may be illustrated by the fact that five of SA's longest surveyed caves are found here accompanied by some of the country's strongest springs together yielding more than 150 million litres daily. This renders the dolomites in the WFS area arguably the most important aquifers in SA.

Owing to the subsequent intrusion of near-vertical, non-dolomitic dykes (consisting mainly of syenite and dolerite), the massive band of dolomite has been broken up into a number of hydraulically disconnected 'compartments'. In total, seven different compartments exist in the WFS catchment varying in size from a few tens of square kilometres to several hundreds of square kilometres.

With groundwater flow dammed up at the lower lying dyke of each compartment, so-called eyes form – standing water bodies of upwelling groundwater. With water overflowing from the compartments into the WFS in much the same way as it would in a tilted ice tray, perennial flow could be sustained in the rivers despite a strongly negative climatic water balance and resulting semi-arid conditions.

Since much of the surface runoff is intercepted fractures, sinkholes and other karst-related conduits in the outcropping dolomite diverting it directly underground, the surface water system is poorly developed resulting in only a few tributaries contributing to flow in the WFS. Early reports of travellers and hunters visiting the area describe how the WFS at some locations disappeared into the underground and reappeared further downstream (Mauch, 1872). While this is typical for karst streams, it was the subject of one of the first recorded water disputes in the area where one particular owner diverted the stream into an adjacent cave leaving downstream users dry. It took the intervention of the then President Paul Kruger to resolve the resulting conflict.

## Pre-mining Use of Dolomitic Water

Soon after the first farmers arrived in the area in 1851, water from some of the karst springs such as the Gerhard Minnebron Eye and the Turffontein Eye was used for irrigation. When spring flow from the latter two sources started to fail in 1911, drying up completely in 2 years, again water disputes arose. This was settled in 1915 by Judge Jeppe deciding that all spring water that has not been used privately by the owner of the land on which the springs occur for a 30-year period preceding his judgment is deemed public and thus available to downstream users. For the water used, however, indefinite water rights were granted ensuring free supply of such water to this date (Jeppe, 1915, 1923).

Similar disputes over the use of karst springs arose near Pretoria, which as capital of the Union of South Africa up until 1932 entirely relied on local dolomitic water. Owing to some farmers diverting water away for their own benefit and reducing the flow of downstream springs, in 1902, a Commission was established to investigate how karst springs operate using the dolomitic compartments in the WFS as case study (Middleton et al., 1904). The findings of this study together with those of the Inter-Colonial Irrigation Commission of 1905 (Wessels et al., 1905) and the Mooi River Commission (1906) (which also investigated dolomitic water in the WFS area) shaped the first Water Act of South Africa promulgated in 1912 (Government of the Union of SA, 1912).

## Gold Mining

Within 1 year after the 1886 discovery of gold in the Witwatersrand, at the present day Johannesburg, gold mining moved westwards occupying large parts of the headwater region of the WFS. This area later became known as West Rand (WR) goldfield. Towns such as Randfontein and Krugersdorp were solely created at the time to house the early gold miners (Erasmus, 2004).

At the WR, the auriferous sediments which underlie the dolomite further downstream are exposed to the surface. While this allowed for relatively easy access to the ore, this was very different at the dolomitic part of the catchment, where large volumes of inrushing water spoiled many attempts to sink shafts through the karst aquifer.

From very early days of mining, a chronic shortage of a suitable labour force proved to be a limiting factor. In order to overcome this problem, a special commission for mining labour was soon established to coordinate recruitment of labourers from all over southern Africa. This system of employing workers from other countries or provinces on short-term contracts became known as ‘migrant labour’. While slowly phased out at some mines, a large part of the current underground workforce in South African gold mines still consists of ‘migrant labourers’ commonly housed in single-sex hostels.

With workforces of 10,000 to over 20,000 people per mine and prostitution being rife near such accumulations of single, sexually active men, the contribution of the migrant labour system to the spread of HIV/AIDS over southern Africa since the 1980s can be considered significant. After a study into the rate of HIV infections in and around the gold mining town of Carletonville (named after the first engineer of goldfields of SA, Canadian born Guy Carleton), this town and its associated township Khutsong apparently were dubbed ‘AIDS capital of the world’ (GFL, 2005; Stoch, 2008). With many of the migrant labourers not returning to their home countries after their contracts expired, the black township of Khutsong experiences an annual population growth of approximately 10% (Spies, 2007). The settlement today is one of the hot spots of political unrest in SA linked to poor service municipal delivery with frequently erupting, often violent riots.

With a sharp rise in the price of gold in recent years, many mines reported a significant extension of their productive life spans in some cases of up to several decades accompanied by planned deepening projects aiming at depths well beyond the 4000 m level

(Campell, 2004; Venter, 2007; Creamer, 2008). In view of the Jordaan report predicting closure of most mines in the area well before 2000, this illustrates the uncertainty of planning in mining-dominated environments (Jordaan et al., 1960; Stoch and Winde, 2010).

## Uranium Production

With the advent of the Cold War in the mid-1940s and the launch of the atomic weapon programme known as the 'Manhattan Project' in the USA, a joint commission from the UK and the USA together with representatives of the Union of South Africa followed reports that gold ore mined in the Witwatersrand contains the much-needed uranium. After screening a large number of ore samples from underground gold mines, the commission came to the conclusion that the South African ally has a large potential to supply the radioactive metal (Taverner, 1957). Following that, the South African government launched a large-scale programme to establish an uranium industry in SA based on existing gold mines producing the metal as a by-product. At one stage, 27 different gold mines provided 14 metallurgical U plants with uraniferous ore of which 5 were in the study area (Stuart, 1957). The newly created Nuclear Fuels Corporation of South Africa (NUFCOR) has, since the inception of the U programme, sold more than 270,000 t of U concentrate rendering NUFCOR the largest, continuous producer of U concentrate worldwide and SA the fourth largest U-producing country during the Cold War period (Creamer, 2007). This facility, too, is located on cavernous dolomite.

Much of the produced U came from mines in the WFS catchment where the gold ore frequently showed above-average U grades. However, compared to grades mined elsewhere, South African ore was regarded as low grade (<0.1 wt%) requiring special extraction technologies not yet invented at the time. The first pilot plant for experimenting with low-grade extraction was built in 1949 at the Blyvooruitzicht GM, while the first fully operational U plant was commissioned in 1952 at the West Rand Consolidated GM near Randfontein, indicating the pivotal role the gold mines in the study area played for the U programme (Stuart, 1957; Taverner, 1957).

Later on, more U plants were built at other mines in the WR and FWR including the Luipaardsvlei GM, the Deelkraal GM, the West Driefontein GM, the Western Areas GM (now South Deep) and the West Wits Operation GMs all feeding U concentrate ('yellow cake') to the enrichment plant at NUFCOR. Following drastic price drops in the early 1980s, many gold mines abandoned U production and no longer extracted the radioactive heavy metal from the mined ore. That, in turn, meant that U was discarded along with the tailings onto so-called slimes dams. Since leaching with sulphuric acid extracted some 90% of U, abondoning uranium production caused a 10-fold increase of U levels in the deposited tailings dams. With an average concentration of approximately 120 g/t U, slimes dams in the WFS catchment are estimated to contain a total of approximately 150,000 t U (Wymer, 1999). Covering a footprint area of several tens of square kilometres, today these slimes dams are a major source of diffuse water U pollution. This is particularly so, as many slimes dams were deliberately placed on cavernous dolomite to facilitate the drainage of surplus pore water for promoting stability and avoiding dam failure (Winde 2006b).

Following a sharp rise in the spot price for U from 2003 onwards, new interest in extracting U from old tailings deposits was sparked. Slimes dams, formerly constituting environmental liabilities that require expensive remediation, quasi overnight, turned into valuable assets (Hill, 2007; 2008b). For example, U contained in the Cooke slimes dam in the upper part of the catchment only in 2007 represented a value of some R 1.6 billion (based on US$ 70/pound $U_3O_8$) (Hill, 2008a).

Dedicated companies, often joint ventures between local gold mines and partners from Australia and Canada, have been established to recover U from tailings. Plans to dispose of the leached tailings centrally at new 'Mega slimes dams' are currently underway accompanied by public resistance.

This all comes at a time when the South African government with active support of the International Atomic Energy Agency (IAEA) embarked on an ambitious nuclear expansion programme (Moodley, 2006; Oliver, 2006). Declaring U a 'strategic mineral' in 2007, a long-term aim of the South African government is to build on its past reputation as a reliable U supplier and become a major producer of nuclear fuel (Anonymous, 2007a).

Furthermore, mothballed shafts of gold mines have been reopened and now operate as dedicated U mines.

Despite a plunge of the U price in 2008 that resulted in the mothballing of a newly opened U mine owned by a Canadian Company, the industry is generally confident that the U demand will continue to increase since nations such as China, India but also the USA plan to sharply increase the number of nuclear power plants to combat climate change. With 25 new U mines predicted to be needed for satisfying the growing global demand by 2025, U mining is likely to expand especially in southern Africa where administrative procedures for new mines are perceived as being resolved much quicker than, for example, in Canada and Australia as other major U producers (Creamer, 2007, 2009). This may explain increased activities of established Australian and Canadian mining companies especially in southern and South Africa.

## Gold Mining Impacts: Dewatering of the Dolomitic Compartments

Stepping back in time, profitability of FWR mines was since inception reduced by incurring high costs for pumping dolomitic groundwater that found its way into the underlying mine void back to surface. Costs are especially high since mines in the FWR are the deepest in the world reaching depths of close to 4 km. This requires high-performance pumps and large amounts of electricity to pump the water to surface. A typical mine today may pay several millions of Rand each month for pumping costs alone. These high pumping costs towards the end of mine's life rendered many uneconomical, resulting in the South African government heavily subsidizing pumping costs of these mines to prevent closure-related job losses and neighbouring, still operational mines from flooding. This changed only recently when the Department for Mineral and Energy (DME, now renamed Department for Mineral Resources) decided to rather use these funds for reducing the ingress of water into the mine voids instead of paying for the much more expensive consequences of such ingress in the form of pumping subsidies (Winde et al., 2006).

Since it was established that volumes of ingressing groundwater increased proportionally to the size of the mine void, some mines suggested to curb the associated rise in pumping costs by 'dewatering' the dolomite aquifers overlying the mine void to remove the source of the ingressing water. This was to be achieved by pumping out more water from the underground void than naturally could be replenished by rainfall. This resulted in the groundwater table of affected compartments dropping by up to 1000 m in places (normally close to the pumping shaft). Further away from the point of abstraction, less dramatic lowering rates occurred, fading to below 1 m at the fringes of the compartments. While the term 'dewatering' suggests that the affected karst aquifers are dry, this is not the case. On average, only 40–60% of the total water stored in the aquifer was pumped out, leaving considerable water volumes still in the 'dewatered compartment' (Swart et al., 2003b). To date, four of the seven dolomitic compartments have been dewatered.

However, since much of the underground karst aquifers were declared governmental water protection areas (under the 1956 Water Act), permission to dewater these aquifers had to be obtained from government first. For factual decision support, an inter-department commission comprising representatives from 10 different governmental departments under the leadership of the Department of Water Affairs ('Jordaan Commission'), from 1956 to 1960, investigated the potential effects of the proposed dewatering, captured in over 20,000 report pages. While acknowledging the adverse impacts of groundwater lowering on existing irrigation farming, the Commission concluded that economical benefits from gold mining will by far outweigh potential agricultural losses and hence recommended the permission of dewatering. The actual permission was granted 4 years later (1964) by which time two compartments (Venterspost and Oberholzer) were already (and thus illegally) dewatered. It is believed that dewatering at such scale and magnitude in terms of areal extent, depth of drawdown, involved pumping volumes and duration is worldwide unprecedented.

### Consequences of Dewatering

When dealing with the consequences of dewatering, a distinction between those anticipated and predicted by the Jordaan Commission and those not expected needs to be made. Anticipated consequences of the large-scale drawdown of the groundwater table included the predicted drying up of all dolomitic springs located in the affected compartments as well as of most boreholes used to supply irrigation water to farmers. In order to compensate farmers for the loss, the water pumped by the mines from underground was supplied to affected farmers via a vast network of partly newly built canals and pipelines.

However, failing crops and fertility problems with animals such as cattle soon raised suspicion that mining had changed the quality of the dolomitic water. Faced with such allegations, the mine's first response was to accuse complaining farmers of libel and irresponsible statements, threatening legal action against some of their representatives. The fact that some farmers indeed tried to use the situation unlawfully for their own advantage made the situation only more difficult for the truly affected community. Since the gold mines at the time not only had a strong political lobby but also provided large parts of the country's tax revenue, employment as well as the much-needed strategic uranium, government tended to side with the mines rendering it even more difficult for farmers to get justice (Stoch et al., 2008).

With farmers proposing that U and possibly associated radioactive pollution may be at the heart of the problem, the mines denied categorically despite having had internal information to their disposal that significantly elevated U levels were found in mine water (Enslin et al., 1958). This attitude of denial and associated efforts to disprove any claim of radioactive pollution was maintained well into the 1990s. It was only in 1997 when the then Minister of the DWAF, Kader Asmal, who reportedly was involuntarily sterilised by the apartheid government applying radiation during a hospital visit, ordered the first comprehensive investigation into the alleged radioactive pollution of the WFS. Since then, many follow-up studies confirmed that U levels in surface and groundwater as well as soil and sediments are elevated. Together with accompanying media reports and increasing political pressure, this resulted in a fundamental change of attitude of many gold mines. The existence or the degree of pollution is no longer questioned and in many cases, mines pro-actively seek means to improve their control over U sources and minimise pollution. Apart from a new generation of environmentally and socially conscious managers having meanwhile taken over, this may also be attributed to changed shareholder behaviour that does no longer tolerate transgressions of the law and environmentally irresponsible behaviour. This together with economic effects of a 'bad press' on shares traded at international stock exchanges and almost instant distribution of relevant information to decision makers worldwide via Internet and telecommunication networks may also have been instrumental in bringing about this change.

Apart from the predicted effects of dewatering, there were also unforeseen, dramatic consequences. Since lowering of the groundwater table allowed for infiltrating surface water to travel further down before reaching the water table, the sub-surface erosion of fine material filling pre-existing cavities in the dolomites resulted in a large number of suddenly appearing sinkholes. Some of them were of such extent that whole buildings, people, roads and cars were swallowed. In one instance, the seven-storey crusher and sorting plant at West Driefontein Gold Mine disappeared completely together with 29 people into a sinkhole with no trace left to retrieve. To date, more than 1000 sinkholes have appeared in the dewatered area, many of them directly in the stream bed of the WFS (Swart et al., 2003b). This, ironically, caused exactly the opposite of what dewatering was originally aimed at, i.e., an increase of water ingress into the mine void fed by stream water and rainwater running directly underground via newly opened sinkholes.

In order to reduce the increased pumping costs, in 1977, an approximately 30-km-long pipeline with a diameter of 1 m (colloquially known as '1-m pipe') was installed to carry the stream flow across the dewatered compartments. The close cooperation between government and GMs at the time is illustrated by the fact that the South African government paid approximately two-thirds of the costs of the pipeline amounting to millions of Rand at the time. However, caused by frequent spillages from the upstream dam that feeds into the pipeline after rain storms, significant volumes of water still bypass the pipeline finding their way into the underlying mine void. In two campaigns in the late 1980s and the early 1990s, a major mining house in the area attempted to reduce this ingress by closing the sinkholes in or near the WFS stream channel with tailings (Swart et al., 2003b). This, however, was frequently unsuccessful since the filled tailings disappeared overnight through openings at the bottom of the sinkholes ('throat') allowing for the uraniferous tailings material to flow directly into the underlying karst aquifer. In some cases, pouring of tailings into sinkholes continued for over a year with the entire daily tailings production of a metallurgical plant over the period being accepted by the receptacles in the cavernous karst. Where sinkholes affected slimes dams, the same process occurred, i.e. U-containing tailings were directly collapsed into the underlying karst aquifer. Owing to significant outflow of (highly polluted) seepage from the base of SDs, the risk of sinkhole formation below tailings dams is particularly high. In one instance, more than 52 sinkholes occurred at a single slimes dam (Stoch, 2008). For a limited period of time, the direct deposition of tailings into caves located on mine property was also practised as a cost-efficient way of tailings deposition.

For any future rewatering of these currently dewatered aquifers, the presence of uraniferous tailings and their potential to adversely affect the future groundwater quality must be considered.

In addition to the occurrence of suddenly appearing and spatially confined sinkholes (the maximum diameter was approximately 150 m), incidences of slowly subsiding dolines affecting several square kilometres-large areas often in densely populated towns also occurred.

Having claimed several lives, this degree of ground instability naturally caused a public outcry with subsequent investigations being commissioned to understand the causes of the problem and prevent further occurrences. As a result a dense network of surface levelling points monitored daily to monthly was implemented. Furthermore, with financial support from the GM industry, a detailed gravimetric survey covering over 400 km$^2$ was conducted. This was overseen by the Geological Survey at the time, heading a specifically established committee [State Coordinating Technical Committee (SCTC) on Sinkholes and Ground Subsidences in the Far West Rand]. Data created since then are mostly archived with little attempts to scientifically evaluate this wealth of unique measurements. This is also true for recorded pumping data during the active dewatering by the mines, which was likened to the world's largest ever pumping test conducted in a karst aquifer. A systematic, comprehensive scientific evaluation of these data with regard to assessing the hydraulic properties of the karst aquifer as well as that of other strata is still outstanding.

With increasing evidence that the large-scale drawdown of the groundwater table was the cause of these problems, government insisted that the mining industry establish a body which streamlines the industry's response to related compensation claims. Up until then, the burden of proof rested with the complainant, rending it costly and time consuming for affected parties to get compensated by the GMs for ground stability-related losses. In response to the state's request in 1964, such body was established in the form of the Far West Rand Dolomitic Water Association (FWRDWA) representing all GMs operating in the dewatered dolomitic area. In many instances, the FWRDWA purchased affected farms creating a large corridor of mine-owned, degraded and largely unused land running along the WFS.

After experiencing the catastrophic consequences of dewatering at the Venterspost and Oberholzer compartments, precautionary measure was put in place before the compartment between the two was dewatered. This included the evacuation and abolishment of a whole settlement (Bank) as well as the diversion of existing railway lines.

To find the 'least unsafe' route over dolomitic terrain for the latter, a specific study was conducted recommending a new course. While this course proved to be safe during the first 2 years of operation when only bulk transport goods were allowed on track, this changed when the first passenger train was commissioned and promptly stuck over a huge sinkhole that had opened right below the railway tracks that very night. Fortunately, no persons were injured.

Despite many efforts to scientifically predict the occurrence of ground movement, a reliable method is yet to be found. Recent sinkhole formations next to the main water reservoir tank of the Carletonville municipality apparently chosen after careful consideration of ground stability aspects illustrate this (Spies, 2007). In contrast, the current necessity to move more than 10,000 households of Khutsong off unsafe dolomitic land is owed to careless planning of 'black' townships during the apartheid era rather than scientific uncertainty. Associated cost estimates are currently at ZAR 2.2 billion (Anonymous, 2007b; Stoch and Winde, 2010) located in the upper part of a non-dewatered compartment where ground movement is not primarily due to mining but caused by a natural drawdown of the water table at the lower end of the compartment.

## Economic Net Balance of Dewatering

After more than five decades or so of active dewatering, a retrospect analysis is still outstanding exploring whether dewatering financially indeed was the best possible option taking all related effects of economic significance such as ground instability into account.

Such analysis should include a reliable estimate of the true volumes of water that could have possibly ingressed into the mine voids without dewatering since previously estimated figures appear to be unrealistically high (Swart et al., 2003b). With less water ingressing than originally expected, decreased costs for pumping would have resulted in reducing the overall 'saving' that could be possibly achieved by dewatering. In this context the argument of the Blyvooruitzicht GM (then Rand Mines) against dewatering should be re-evaluated which argued that adding sawdust to the re-circulated pump water would soon clog the tight fissures along which dolomitic water migrates over thousands of metres from the cavernous aquifer to the mine void. This is in addition to suggestion that reducing the water table elevation in the karst aquifer by a few metres on average would do little to reduce the ingress driven by a hydraulic head of thousands of metres (Irving, 1958).

The realistically estimated savings due to dewatering should then be compared to the total costs incurred directly and indirectly by the mines themselves as well as by third parties such as the agricultural sector, local municipalities and government. This includes the loss of lives and damage to infrastructure due to ground instability, costs for replacing infrastructure as well as associated devastation of land, devaluation of properties and loss of agricultural income, to name only some of the relevant aspects. Since dewatering of aquifers is still a considered option elsewhere, a sober analysis of alternatives and the true costs as incurred over half a century of active dewatering, including those externalised to society and the environment, may hold valuable lessons for better management of today's mining operations.

## Mined Out: Post-closure Scenarios

After more than 100 years, active deep-level mining ceased in the WB in the late 1990s allowing water to naturally fill the underground mine void. Owing to a process known as 'acid mine drainage' (AMD) which liberates the accumulated metals from unmined ore bodies in these voids, the gradually rising void water is often highly contaminated. Together with seepage from large deposits of mining residues such as tailings dams and rock dumps that cover a significant proportion of the catchments, such water is often extremely acidic and displays high levels of salts such as sulphates as well as a range of toxic heavy metals including radioactive ones. Approximately half a decade after underground pumps were switched off at the Western Basin, the mine water finally reached the surface and started to overflow into the environment (termed 'decanting'). Ironically, instead of impacting on the WFS in whose catchment most of the acidic mine water was generated, much of it crossed the continental divide via underground mining infrastructure and discharged into a small stream that runs towards a UNESCO World Heritage Site known as Cradle of Humankind at the Sterkfontein Cave complex. Having recently been declared a UNESCO World Heritage Site ('Cradle of Humankind' since early hominids were discovered there), the caves initially were thought to be ultimately flooded by the decanting mine water jeopardizing its World Heritage Status only months after it had been upgraded for millions of Rand to an international tourist attraction (Fourie and Associates, 2004).

Since no preventative measures had been taken to address the expected and inevitable flooding of the mine void, the decant had devastating consequences for the receiving environment. Apart from severely affecting the ecology of the small stream receiving the mine water, it was also linked to a sudden surge of deaths of animals such as lions and antelopes in a Game Reserve located a few kilometres downstream of the decant point. With uranium levels tens of thousands of times above natural background values, the National Nuclear Regulator declared the decant site radioactively contaminated.

After a governmental directive to treat the decanting mine water to acceptable standards and to divert it to the WFS met resistance of downstream residents in the WFS catchment, the water now runs north again frequently exceeding stipulated upper limits for selective quality parameters such as sulphate and uranium concentrations. Currently efforts are underway to treat this water together with effluents from other flooded mine voids in the Central and East Rand and sell it on a commercial basis to potential users including Rand Water as the most important water service provider in Gauteng. It may also include Platinum Mines in the Rustenburg area some 80 km to the northwest which chronically suffer from production-limiting water shortages.

Compared to the West Rand, the size of the mine void created in the Far West Rand further down in the catchment is significantly larger. Together with the abundance of dolomitic water, this results in much larger volumes of mine water potentially decanting from the voids decades after mining has ceased in the region in approximately 30–50 years from now. Judged by the dire consequences the decant caused on the West Rand, a similarly uncontrolled and unmitigated event in the Far West Rand could be disastrous, especially for the booming university town of Potchefstroom that depends entirely on surface water largely sourced downstream of the mining area.

## Uranium Pollution and Health Risks

These future worst case scenarios are unsettling for many members of the general public already concerned by reports about current levels of radioactive pollution. Dating back to the 1960s, when farmers first suggested that radioactive pollution may be responsible for failing crops and livestock problems (Retief and Stoch, 1967), uranium pollution has been denied by the mining industry despite being in possession of data as early as the late 1950s (including governmental data in the Jordaan report) that showed the opposite (Jordaan et al., 1960). These data were later confirmed by internal, confidential studies during the late 1980s and early 1990s conducted by the Chamber of Mines Research Organisation (COMRO 1990, 1991; Pulles 1991) and individual mines (Deelkraal Gold Mine, post-1990; Slabbert, 1996).

It was, however, not before apartheid was abandoned and the first democratically elected government of SA installed that public investigations were considered. It was personal efforts of a resident of the catchment who represented the farmers back in 1962 that convinced the then Minister of the Department for Water Affairs and Forestry (DWAF), Prof. Kader Asmal, a veteran of the anti-apartheid struggle who suffered radiological sterilisation inflicted by the apartheid regime, for the first time to publicly investigate the allegations (Stoch, 2008).

Following a screening survey on radioactive pollution in all gold mining areas, in 1997, a large monitoring project commenced systematically analysing hundreds of water samples from the WFS and the Mooi River catchments for U and other radionuclides (Kempster et al., 1996; IWQS, 1999). However, with representatives of the mining industry exerting undue influence on the study and especially the way results were interpreted (the CoM representative at the time 'edited' the final report of DWAF re-writing approximately 80% of the original text before it was released to the steering committee and the public), various scientists finally rejected the findings of the study, which concluded that generally no water-related risks caused by U exist (Stoch, 2008).

This study, however, recommended a follow-up investigation into the potential pollution of sediments that was subsequently conducted by the CSIR in 1999 (Wade et al., 2002). In contrast to the first study, this report indicated a significant degree of U contamination of sediments in the WFS, likely to pose a risk to water users. Of particular concern were findings in a shallow farm dam downstream of the mining area where environmental immobilisation and associated reconcentration of U (geo-magnification) had resulted in U being accumulated to levels exceeding tailings and ore concentrations of the radionuclide by up to an order of magnitude. A dedicated follow-up study by the Council for Geoscience (CGS) commissioned by government aimed at quantifying the associated risks concluded that U may be released back into the stream water under a number of plausible environmental scenarios. This, in turn, triggered a larger scale study funded by the Water Research Commission of SA (WRC) to investigate the sources, pathways and mechanisms of mining-related U pollution in the WFS catchment as well as possible resulting risks (Coetzee et al., 2006).

Concentrating on the chemo-toxicity of the heavy metal U, the report concluded that U pollution of both water and sediments may pose a significant health risk to water users. Disagreeing with the underlying risk assessment methodology, the NNR, as member of the steering committee, insisted on the inclusion of a disclaimer to that effect into the final report, indicating that the NNR will conduct its own investigation. After a considerable delay in publishing the report due to the intervention of a gold mine, prompting the Department for Minerals and Energy (DME) to place a moratorium on the document, the report was finally released in 2006. This was mainly thanks to the repeated insistence of the same environmental activist that represented a family in a claim against the aforementioned gold mine together with an environmental journalist who repeatedly reported on the issue (Liefferink, 2008). Hailed as the first evidence for the *democratisation of science in SA* by a CSIR researcher at the time, the finally released WRC report 1214 received much media attention as well as hostile reactions from some quarters of the mining industry (Turton, 2008).

The announced investigation of the NNR finally commenced in late 2006 conducted by a German consultancy that oversaw the rehabilitation of the former Wismut uranium-mining region in East Germany on behalf of the Environmental Department of the German Government. Using a radiological dose assessment methodology, the resulting report confirmed that U-polluted water as well as sediments may pose severe radiological health risks especially for exposure scenarios related to the consumption of contaminated agricultural products (Barthel, 2007).

Again this report received a large degree of attention in national and even international media additionally magnified by the initial reluctance of the NNR to release the report to the public as well as preventing its author from presenting the results to a scientific conference. On parliamentary level, pertinent questions were directed to relevant Ministers putting increasing political pressure on responsible departments to deal with the problem. The announcement of government to embark on a national nuclear expansion programme further added to the urgency of laying public concerns about radioactive pollution to rest. As a consequence, government in a joint effort between the DWAF and the NNR, in late 2007, appointed an international specialist task team (STT) to investigate possibilities to rehabilitate the WFS and address radioactive pollution.

With evidence mounting that mining operations resulted in large-scale U pollution, the mining industry finally changed its attitude and now no longer denies the existence of pollution. In collaboration with concerned citizens, GFL as major mining house in the area established the WFS Action Group (WAG) and conducted a large-scale sediment sampling programme confirming the existence of radioactive pollution (WAG, 2007). At the same time a number of small, uncoordinated studies commenced with non-specialist arbitrarily collecting grab samples of water, tailings, sediments as well as meat, vegetables and milk. With methodological shortcomings and often flawed interpretation, this further raised the number of alarmist media reports while not adding much scientific value (NNR, 2007; Durandt, 2008). Currently more systematic efforts are underway to quantify the degree of U pollution for various media (water, sediment and biota) (Winde, 2010a, b) and to analyse for the different types of sources through which U is released into the environment (Winde, 2005; 2006a, b, c, d).

However, to date, little or no epidemiological data exist that point to a possible relation between U pollution and adverse health effects in exposed residents. The latter are mainly found in informal settlements where untreated mine and stream water are frequently used for domestic purposes due to lacking alternatives. Additionally suffering from the exposure to a range of contamination sources including substandard sanitation, indoor and outdoor air pollution as well as poverty-related stressors such as malnutrition, lack of medical care and an above-average rate of HIV infections, the most exposed population is frequently also the most vulnerable. However, with U-related health problems such as cancer often taking decades before becoming manifest, many of the exposed migrant workers may long have left the area before symptoms occur. The generally high residential mobility in mining areas coupled with a number of poverty-related masking effects such as AIDS-related diseases and premature deaths as well as a generally risky behaviour amongst migrant mine workers (alcohol and drug abuse, etc.) may prove it difficult to establish any statistically significant relationship between U exposure and adverse health effects in such areas.

However, this was quite different in an arid area of the Northern Cape of SA where the mobility amongst the rural population is limited. Triggered by an observation of a medical doctor at Stellenbosch that many of his leukaemia patients came from a certain area in this Province, a 1997 study established a significant geostatistical link between haematological abnormalities related to leukaemia in over 400 residents and the (geologically elevated) U levels in the borehole water used for drinking (Toens et al., 1998).

Despite the fact that some governmental officials that served on the steering committee of this project later also advised the IWQS study, none of the rather worrying findings from the Northern Cape were brought to the attention in the WFS project. In fact, to most involved researchers, the very existence of such a pertinent study was unknown. This might partly be explained by the fact that prior to publication the original project title was changed by removing the two crucial keywords ‘uranium’ and ‘leukaemia’, rendering it difficult for anybody interested in either aspect to find the document by using a keyword search. Despite several follow-up studies confirming the elevated U levels as well as the persistent use of U-polluted water for domestic purposes in many settlements of the Northern Cape, no further action has been taken up until now (Wullschleger et al., 1998; Sekoko et al., 2005; Van Wyk and Coetzee, 2008).

With large cohorts of former workers of closed eastern European U mines becoming available for epidemiological studies after the collapse of communism in eastern Europe, scientific evidence is mounting that health risks associated with U exposure might have been underestimated (for a selection of relevant literature, see Winde, 2010a). This is also indicated by the latest research into health effects of depleted uranium (DU) which at large scale was first used in ammunition during the first Gulf War in 1990 as well as in the subsequent Balkan wars and the second Gulf War. Having been linked to the ‘Gulf War Syndrome’ from which many veterans of these wars suffer, it is now suggested that U – as all elements with high atomic numbers – once incorporated in the human DNA may excessively absorb natural $\gamma$-radiation triggering cell mutations and subsequently different types of cancer (Busby, 2005).

The French project ‘Environhom’ dedicated to researching effects of low-dose, long-term exposure to radionuclides typically found that U affects not only the kidneys as long assumed but also the brain to the same extent (IRSN, 2005). The Neurotoxic effects of U were confirmed by clinical studies with Gulf War veterans who retained DU material in their bodies and showed significantly lowered cognitive performance. Environhom further concluded that effects of low environmental radionuclide concentrations cannot simply be predicted by linear extrapolation of high-dose event data gathered, for example, in survivor studies of the Hiroshima bombing. Incorporating epidemiological data from a cohort of 59,000 former Wismut mine workers that became available after U mining in East Germany was abandoned in 1990, German researchers found that rates for liver cancer are up to 70 times higher than those predicted by currently used models (Jacobi et al., 1997). Furthermore, U was recently discovered to also act as an endocrine-disruptive compound (EDC) impacting adversely on hormonal balances in organisms as well as on the immune system (Raymond-Wish et al., 2007). Since many people in informal settlements who use untreated U-polluted water already suffer from a compromised immune system due to a range of factors including HIV/AIDS, this is of particular concern in the study area (Winde, 2010b).

In view of the fact that almost all currently existing guideline values for U in drinking water worldwide, including the World Health Organisation (WHO), the Environmental Protection Agency of the United States of America (US-EPA), Health Canada, to name but a few, are based on its nephrotoxicity as found in short-term, high-dose exposure experiments with rats and rabbits (Von Soosten, 2008), the newest findings on U toxicity may indicate a need for reviewing the appropriateness of these guidelines. In doing so, the increased vulnerability of the large proportion of the global population in Third World settings which is affected by poverty-related stress should be taken into consideration. This particularly so since developing countries are most likely the ones to experience the most pronounced increase in least regulated U mining.

## Loss of Institutional Memory

Looking back at over 100 years of mining and its impacts on the people and the environment, it appears that the first class infrastructure and level of industrialisation which SA owes to the gold mines separating it from many other African states came at a price. However, much of the price was either not known at the time or discounted since costs could be passed on (‘externalised’) to the receiving environment, downstream users and/or future generations (Adler et al., 2007). With the advent of sustainability as a core concept in modern day politics, such externalisation of costs is no longer acceptable to society at large. Amongst others this is illustrated by the new Water Law of South Africa introduced in 1998. In contrast to its predecessor from 1956 that was aimed at promoting mining and industrialisation, the new Act abandoned the concept of privately owned water altogether and strongly promotes equitable access to water by all members of society while ensuring environmentally sustainable use. At the same time, the Act aims to decentralise water management and delegate decision-making power to so-called catchment management agencies (CMAs) at local and regional levels. The Act also recognises the need for a more integrated approach to water management, reconciling environmental water requirements ('ecological reserve') with human demands through a process of licensing the use of water.

However, current challenges such as loss of skills and high staff turnover at the implementing departments frequently render it difficult to retain the required level of competence and effectively enforce the modern and advanced legislation. As a consequence, many core functions of the Department are now outsourced to private consultants often consisting of former DWAF employees frustrated by an affirmative action-based career policy who are now selling back their expertise to the Department at much higher rates. Despite the associated loss of functions, the number of DWAF employees rose from approximately 6000 in 1994 to close to 20,000 in 2008 further adding to a low-cost efficiency (Von der Westhuizen, 2008). Since salary budgets are frequently overstretched, little room exists to retain or attract much-needed, skilled professionals such as engineers and scientists to combat critical shortages of core personnel.

Together with the experienced loss of expertise, the knowledge about existing data often also disappears rendering affected departments vulnerable to unnecessary repetition of work, wrong decisions and overall poor law enforcement levels. The fact that some 22,000 pages accompanying the report of the Jordaan Commission could for a long period not be traced at the DWAF may illustrate this point. In the absence of knowledge as to why, for example, long-standing committees such as the SCTC have been established in the wake of catastrophic dewatering, government recently allowed this committee to be dissolved, further contributing to what some term 'institutional amnesia'.

The phenomenon is, unfortunately, not only confined to government but also affects the highly dynamic mining industry. Although the mines are commonly less affected by stringent affirmative action regulations or lack of resources, they often lose expertise and data due to frequent changes in ownership, amalgamations and associated restructuring as well as the natural retirement of experts (Stoch and Winde, 2010).

In an effort to combat this trend, a library was established by the Water Research Group of the North-West University (NWU) in Potchefstroom aimed at compiling pertinent sources in the form of published but most importantly also unpublished literature, reports, data, newspaper articles, maps, graphs, photos and digital information. Open to all interested parties via Internet access, this database aims to assist scientific research through preserving relevant knowledge and data of the area. The particular challenge in this regard is the fact that data are held by different institutions with little or no efforts to consolidate all pertinent information into a comprehensive and easily accessible database. It is believed that the density and quality of data gathered over more than 100 years is unrivalled and to a large extent was affordable only due to the existence of some of the world's richest mines in the area. This includes more than 20,000 borehole logs reaching up to 4000 m below surface, high-density gravimetric surveys covering over 400 km$^2$, records of daily pumping volumes and water level monitoring spanning more than five decades accompanied by associated meteorological data and pertinent flow gauging time series, the results of a 4-year in-depth investigation of the hydrological conditions, monthly water quality data of the DWAF for over 40 stations in the area in addition to thousands of measurements made by each of the operating gold mines over the past decades, a large number of U-related studies, long records of seismicity observations, ground movement levelling data and detailed surveys of over 1,000 sinkholes (depth, shape, width) that occurred after dewatering. This is complemented by over 100 years of pumping data from Rand Water operating in an 'un-dewatered' compartment linked to the area as well as some unique data generated by investigations into karst hydraulics more than 100 years ago. In recent years, a number of high-resolution airborne surveys of $\gamma$-radiation, infrared, radar and lidar data have been added to this wealth of data at considerable costs.

It is believed that combining all data in a central and publicly accessible database will greatly assist not only pertinent research but also future water management in a region which not only is one of the most densely populated in SA but also may sooner than any other experience severe water shortages.

## The Way Forward

In view of the devastating consequences the uncontrolled outflow of polluted mine water from the flooded mine void in the West Rand goldfield had since 2002, it is of utmost importance to avoid a similar incidence in the Far West Rand where the much larger mine void and higher groundwater recharge rates would result in significantly more polluted water decanting into the environment. This could have disastrous consequences for the downstream community of Potchefstroom whose water resources would be affected. Key aspects of mine closure and rewatering-related research include the prediction of inflow rates and the associated time it will take to flood the large system of interlinked mine voids during which period the water availability to the downstream municipality of Potchefstroom might be drastically reduced. After the dewatered dolomitic compartments are filled again, it will be crucial to reliably predict where, how much water of what quality will be issued and where the decant points are located. Also of interest is the question of how far the rising water levels may trigger renewed ground instability in the form of potentially catastrophic sinkholes as observed during a brief water table recovery triggered by a wet period in the mid-1970s (Swart et al., 2003b). This includes the determination of critical levels above which water should not rise to prevent ground instability as well as contact of groundwater with large volumes of tailings deposited in the upper part of the cavernous zone. Furthermore, the possibility that natural stratification will allow for clean water float on top to be harvested while keeping polluted water at deeper parts of the mine void should be investigated. With a final hydraulic head of more than 4 km in places acting on a distorted geological underground, the possible occurrence and magnitude of rewatering-related seismicity especially during the initial adjustment phase (similar to effects caused by the filling of large dams) should also be studied (Durrheim et al., 2006).

However, reliable predictions of rewatering-related effects will require a much improved understanding of the general hydrology of the affected karst aquifers. With arguably the world's largest man-made drawdown of groundwater conducted in the study area and huge amounts of pertinent data, such research could draw from a partly unique set of data. The development of a complex hydrological karst model will be crucial for predicting effects of rewatering on water quality and availability as well as potential flow pathways and decant points.

At the same time it is urgent to assess as to how far the currently present pollution of water and sediments especially with the radioactive heavy metal uranium poses a health risk to local residents and/or downstream users. This in particular true as the latest findings suggest that toxic effects of U may be more varied and severe than previously assumed (Winde, 2010a). Investigations are required to quantify the extent to which U may move along the food chain adversely affecting consumers. With relevant data dating back to the 1960s and suitable settings being available for in situ investigations, a site-specific, measurement-based approach needs to be followed as opposed to the application of generic models developed elsewhere. So far most radiological risk assessments conducted in the study area are based on somewhat arbitrarily chosen transfer factors from different sources found to vary by up to several orders of magnitude (IWQS, 1999; Barthel, 2007). This should be complemented by epidemiological studies on the effects of prolonged exposure especially of people living in informal settlements to U pollution. This needs to include research into relevant behavioural patterns and socio-economic conditions of the most affected user groups.

In view of current efforts by government to remediate the Wonderfonteinspruit system which is still affected by ongoing pollution, it is important to investigate possible means to control the different sources of U pollution (DWAF, 2007). This may include the design of cost-neutral and long-term sustainable water treatment technologies (active and passive) for cleaning mine effluents. For diffuse sources such as slimes dams or sinkholes and karst receptacles filled with uraniferous tailings, the interception of transport pathways (e.g. through installing permeable reactive barriers) may prove to be more efficient than direct source remediation. While reducing the input of contaminants is likely to translate into improvements of the quality of surface waters, this may be different with polluted sediments found in especially wetlands and dams along the WFS as well as larger groundwater bodies. Both media may stay contaminated for much longer periods and may thus require special remediation technologies. In all cases, the sensitivity of dolomitic ground and aquifers is to be considered before any cleanup is attempted. For sediments in areas where direct ingestion can be excluded as a potential way of human exposure, intervention should only be considered once evidence for significant release of accumulated contaminants into the water column under plausible scenarios has been established with reasonable scientific certainty. Otherwise adverse effects associated with remediation such as the destruction of existing wetlands through dredging contaminated sediments or creation of sinkholes by removing protective sediment layers may outweigh potential benefits.

To avoid economic collapse and associated ghost-town scenarios following the inevitable cessation of mining in the area, the development of long-term visions and strategies to replace mining as main economic driver in the area is needed. Winde and Stoch (2010) identified a number of opportunities in the area centring around the abundance of water in the area. This includes the usage of the cavernous dolomite for storing large volumes of water underground where it is protected from excessive evaporation, which accounts for almost one-third of all water flowing in the Vaal River being lost to the atmosphere (calculated from data provided in DWAF, 2008). In order to increase stored groundwater resources, the concept of artificial recharge could be applied using not only existing infrastructure such as mine canals and shaft but also sinkholes to intercept storm water runoff and divert it underground if necessary after prior (passive) treatment. Another project proposed includes the use of stored groundwater for underground generation of hydropower, based on a pumping scheme that utilises day–night differences in electricity tariffs. This could possibly be assisted by using remaining underground mine infrastructure including shafts, pump chambers and pipelines. With rock face temperature increasing to approximately 60°C, deep mine water may also be used as a source for geothermal energy (Winde and Stoch, 2010).

Owing to their proximity to Gauteng Province as largest urban agglomeration in SA, such water could be used for augmenting water supply of a region with one of the most negative water balances in the country (i.e. much more water used than is naturally available). The DWAF investigated the possibility of using this dolomitic water as emergency supply for the PWV metropolitan area (Pretoria–Witwatersrand–Vereeniging, now known as Gauteng Province) as early as 1971 (Enslin and Kriel, 1971). While a drought period in the early 1980s triggered a series of follow-up studies, effects of the large-scale dewatering and current levels of pollution so far frustrated all plans to utilise the rich dolomitic water resources at a grander scale (Vegter, 1983; Conelly and Rosewarne, 1984). It was only recently that efforts to better manage the increasingly important karst aquifers have been revived (DWAF, 2005).

In order to overcome the environmental and economic threats posed by century-old mining, it is indispensable to establish a trust-based collaboration between all major role players in the area, i.e. government, the mining industry, local municipalities as well scientists. Only by constructively engaging all major stakeholders, the current fragmentation of research and rehabilitation efforts can be overcome resulting in a more harmonised and thus cost-efficient approach. However, owing to historical burdens such as secrecy and denial in the past, the required trusts cannot be established overnight. Examples of major mines in the area engaging directly with concerned residents on pollution issues and pro-actively implementing measures for curbing future contamination are signs that such collaboration can be achieved. With some three to five decades left of active mining, sufficient time remains to gather the relevant data and properly prepare for a prosperous post-closure period by turning water into the new (blue) gold.

## Summary and Conclusions

The study area exhibits some of the deepest and richest gold mines on earth of which – as absurd as it may sound for a semi-arid area – nearly drowned due to an abundance of underground water. However, after deep-level mining managed to sink shafts through the water-bearing dolomites, this abundance of water soon ceased once large-scale dewatering was implemented as a matter of policy. Consequences included the drying up of springs and boreholes that used to drive a thriving agricultural sector as well as unforeseen ground movement in form of catastrophic sinkholes claiming human life as well as causing damage to infrastructure and widespread land degradation continuing to this day.

In addition to partly irreversible changes in surface and underground hydrology, the mining of gold also caused the pollution of water, soils and sediments with the radioactive, heavy metal uranium that frequently accompanies gold in the mined ore bodies. In fact, U levels in the ore bodies of the study area were such that local gold mines for long periods during the Cold War supplied U for the atomic weapons programme of the USA. Surrounded by secrecy in those days, the pollution associated with the production of U, especially of water supplied to local farmers in compensation for water lost through dewatering, was initially denied and complaining farmers were accused of making 'irresponsible and dangerous statements' (Stoch, 2008). Enjoying the political support of the Government at the time, the gold mines as economic backbone of the South African economy and U suppliers of strategic military importance maintained this denial for decades to come. This attitude continued largely unabated despite the fact that the mining industry had initiated internal research that showed the contrary as early as the late 1950s (Enslin et al., 1958).

Increasing evidence gathered since 1997 through a number of investigations funded by the newly elected, first non-racial and democratic government into the alleged radioactive pollution resulted in the establishment of a firm body of undisputable evidence of mining-related U pollution affecting surface as well as groundwater resources including the associated sediments and soils. While the levels of U pollution are generally low compared to many other U-mining areas worldwide (there are, however, some exceptions), the continued discharge of large U loads over long periods of time (decades) and the direct, long-term exposure of vulnerable, mainly poor people to polluted water due to lacking alternatives are reasons for concern. This in particular true as the latest findings indicate that U may display a much broader variety of toxic effects than previously thought. Since poor people living in informal settlements often experience a lack of basic medical care as well as the effects of stressors such as air pollution, malnutrition, poor sanitation and infectious diseases including HIV/AIDS, the population group that is most exposed to U pollution is also the most vulnerable. Together with the new findings on U toxicity, this fact may necessitate to review the current U guideline value for drinking water in SA which is the highest in the world, exceeding the newly proposed limit for the European Union by a factor of 7.

With environmental activists increasingly publicizing the scientific findings in sometimes sensationalizing news media and thereby alerting the general public, the attitude of the mining industry recently changed considerably. Acknowledging their responsibility for the caused pollution in line with their corporate image, especially the larger mining houses now frequently engage directly with the public as well as the regulating authorities to address the issue pro-actively.

Since active deep-level gold mining in the Far West Rand is predicted to continue for another few decades, enough time is available to address the challenges arising from the closure of mines and the subsequent flooding of the mine void and dewatered karst aquifers. Recent examples from the mined-out West Rand goldfield where highly polluted water from the flooded mine void was linked to the sudden death of dozens of animals in a downstream Game Reserve indicate the potentially devastating effects a similarly uncontrolled decant event could have in the much larger Far West Rand mining area (Du Toit, 2006).

A number of research needs have been identified to avert such worst case scenario including addressing the loss of institutional memory that affects many regulatory authorities as well as gold mines. Furthermore, a consolidation of the many isolated data held by different companies, departments, municipalities, consultants and the various research institutions into a comprehensive database would be a first step to overcome the fragmented and uncoordinated manner in which research is currently conducted.

Establishing concerted efforts between the mining industry in conjunction with government and the affected public and scientists is regarded as crucial for successfully preparing for the challenges associated with the inevitable cessation of mining. A number of water-centred options have been identified in order to turn perceived liabilities related to historical mining into future opportunities. With a recently much improved interaction between mines, scientists and the public as well as support from the regulating authorities, this may not remain a vision only.

The problems mentioned here are, of course, by no means exhaustively explored and many more facets still deserve attention. It is, however, hoped that the scale and the type of topics presented ranging from hydrological and hydrochemical processes to epidemiological and health issues as well as legal–administrative aspects are relevant to many other areas worldwide facing similar challenges relating to mining in karstic environments. This in particular true, since globally mining still expands and will continue to do so for the foreseeable future especially in developing countries. A point in case is uranium mining that currently experiences a global renaissance owing to efforts to combat climate change.

Since more than half of the drinking water worldwide is drawn from karst systems, it is hoped that lessons learnt in the study area may add to an improved understanding of the complex karst hydrology and how mining impacts can be minimised in order to ensure a sustainable use of the limited water resources.

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# Arsenic Distribution and Geochemistry in Island Groundwater of the Okavango Delta in Botswana

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Nelson Torto, and Sorcha Diskin

**Abstract**

Groundwater samples were collected along an island transect in the Okavango Delta, Botswana, in 2007. A 1000-fold increase in arsenic concentration was found along the transect over a distance of 250 m. Arsenic was positively correlated to conservative elements (Na and Cl), electrical conductivity, alkalinity, DOC, pH, potassium and sulfate and negatively correlated to nitrate. Results from this work suggest that the enrichment of As in the island groundwater of the Okavango Delta is a result of a complex interplay between (1) concentration by evaporation/transpiration; (2) reductive dissolution of Fe oxyhydroxides, masked by reprecipitation; and (3) competitive interaction between $HCO_3^-$ and As for the same sorption sites as pH increases. The predominant process controlling the very elevated levels of arsenic in the island center groundwater is probably the effect of the evapo-transpiration. However, it is proposed that reductive dissolution of oxide and hydroxide of minerals containing Fe and Mn is the initial step for the release of arsenic from the sediment to the groundwater although there was no correlation of arsenic with iron or manganese due to reprecipitation of oxides of these metals.

**Keywords**

Arsenic • Groundwater • Okavango • Wetland

## Introduction

Arsenic in groundwater received global attention due to recent studies in Bangladesh and neighboring West Bengal, India (Chatterjee et al., 1995; Das et al., 1995; Matschullat, 2000; Welch and Stollenwerk, 2003), where arsenic was found at concentrations above the World Health Organization (WHO) recommended threshold for human consumption, currently set at 10 μg/L. Evidence shows that high-As groundwater is often associated with reducing conditions prevalent in alluvial and deltaic environments (Sengupta et al., 2004). Occurrence of As enrichment in Bangladesh groundwaters shows a close relationship with the geomorphological units and As enrichment is mainly restricted to the Holocene alluvial aquifers at shallow and intermediate depths (BGS and DPHE, 2001).

The issue of elevated arsenic in groundwater of the Okavango Delta in Botswana was first raised

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during the second phase of the Maun Groundwater Development Project (MGDP; Department of Water Affairs (DWA), 2003). In that same year, a study of arsenic in water and sediments from boreholes being drilled by the government for local water supply was conducted (Huntsman-Mapila et al., 2006). In 2007, the authors conducted a study of the horizontal change in the concentration of arsenic in shallow groundwater along an island transect in the Okavango Delta. This chapter presents new physico-chemical analyses of shallow groundwater and surface water samples from the Okavango Delta in order to investigate the distribution of arsenic in groundwater of the Okavango Delta and to examine the interactions of arsenic with other physico-chemical parameters. A discussion on release mechanisms of arsenic in the Okavango island groundwater is also presented.

## Geohydrological Background

The Okavango River (Fig. 1), originating in Angola, discharges about 10 km$^3$ of water onto an alluvial fan each year, augmented by about 6 km$^3$ of rainfall, which sustains about 2500 km$^2$ of permanent wetland and up to 8000 km$^2$ of seasonal wetland. Geomorphologically, the Okavango Delta is a mosaic of flat broad floodplains and round to shapeless islands ranging in size from several square meters to 500 km$^2$ (Wolski and Savenije, 2006). Interaction between the surface water and the groundwater in the Okavango strongly influences the structure and function of this wetland ecosystem (McCarthy, 2006). The annual flood occurs during the dry winter season when floodwaters originating from the Angolan Highlands inundate the Okavango Delta. At this time, surface water levels in the Boro River (Fig. 1) increase and the water infiltrates the predominantly sandy soil and flows toward island centers. There is therefore a net flow of groundwater toward island centers (McCarthy, 2006). This groundwater flow is driven by evapo-transpiration by the riparian vegetation and has been modeled by Wolski and Savenije (2006). The island groundwater reservoir is transpired into the atmosphere and the water table is steadily lowered. Salt accumulation in this shallow groundwater system can also be observed (Bauer et al., 2006a, b; McCarthy and Ellery, 1994; Zimmermann et al., 2006).

Accumulation of dissolved salts in this groundwater leads to precipitation of solutes (mainly of silica and calcite) in the soils beneath island fringes and the islands grow by vertical expansion (McCarthy, 2006; Zimmermann et al., 2006). Evapo-concentration can trigger a number of geochemical reactions, most importantly mineral precipitation and de-gassing of carbon dioxide (Bauer-Gottwein et al., 2007). Minerals accumulate in the groundwater beneath an island center, and this impacts on the vegetation, leading

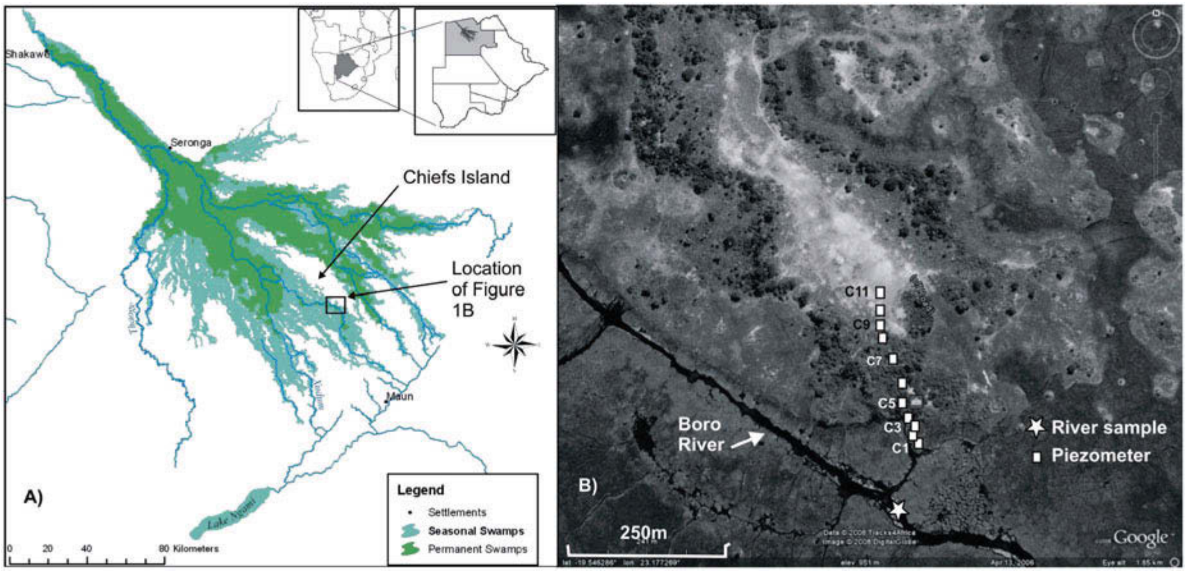

**Fig. 1** Map of the Okavango Delta (**a**) with photo of island transect and sampling sites (**b**)

ultimately to barren island interiors. Dense saline brine thus produced subsides under density-driven flow (Bauer et al., 2007). By the use of Cl as a conservative element, Ramberg and Wolski (2008) found the concentration factor between central island groundwater and surface water of 500–1000. The central island groundwater is dominated by Na, bicarbonate, and dissolved organic matter with a depletion of Ca, Mg, silicate, and K probably which precipitate as calcrete and clays, typically found in the island soils.

Groundwater investigations under islands of the Okavango Delta have included the work of Bauer et al., 2004; Fernkvist and Lidén, 2003; Heusser and Langer, 2004; McCarthy, 2006; Zimmermann et al., 2006, where boreholes have been drilled or piezometers installed.

## Methods

### Site Description and Field Sampling

Groundwater was sampled along an island transect adjacent to the Boro River (Fig. 1). The island becomes surrounded by water during high flood years and is approximately 400 m × 1500 m in size. This transect of piezometers is referred to as the "AB transect" by Wolski and Savenije (2006) and Wolski et al. (2005), the "ORC island" by Bauer-Gottwein et al. (2007), and the "island transect" by Mladenov et al. (2008). Groundwater piezometers labeled C1 to C7 are located in the riparian fringe. The island's center is covered by salt-tolerant grass species and is underlain by fine- to medium-grained sand with a minor fine fraction comprised of amorphous silica and carbonates as described by McCarthy and Ellery (1994). Groundwater piezometers sampled in this region, C8 (at 140 m from edge) to C11 (at 240 m from edge), are referred to as being in the "island center."

Groundwater samples were collected from 11 piezometers (C1–C11). The piezometers are made of 25 mm PVC pipes installed in hand-augered holes, 2–11 m deep. The bottom part of the pipes was slotted and covered with several layers of filter material. The piezometers are located at the edge of the island to its center (Fig. 1) over a distance of approximately 240 m. The piezometers were pumped dry three times prior to sample collection. Surface water samples were collected from the Boro River.

Samples were collected in January 2007 and March 2007. Heavy rains fell in February and it was noted that during the second sampling, the groundwater level at the center of the island was close to the surface. pH, temperature, dissolved oxygen (DO), electrical conductivity (EC), and alkalinity measurements were taken immediately in the field. Readings of pH, temperature, DO, and EC were taken in situ where possible or taken immediately after collection. Hanna 991001 pH and temperature meter, YSI 85 DO meter, and Hanna HI 9033 conductivity meter were used. A 250 mL sample was filtered through a 0.45 μm filter and acidified with 0.5 mL concentrated HCl for cation analysis. Field blanks (deionized water) were filtered and acidified as samples. Anion samples were filtered but not acidified. All water samples were collected in HDPE or borosilicate bottles and refrigerated until analysis. All glassware and plasticware were acid cleaned and rinsed with deionized water.

Sediment samples were collected when the piezometers were installed using an auger. Samples were collected at 0.5 m intervals and stored in plastic bags in the freezer until analysis.

### Laboratory Analysis

#### Water Samples

The UV absorption is a useful approximate measure of dissolved organic carbon (DOC) in the water of the Okavango Delta and absorbance at 280 nm in surface water has been found to give the best correlation (Mladenov et al., 2005; 2008). This method has been used (Huntsman-Mapila et al., 2006; Mladenov et al., 2008) for the determination of DOC. A UV–Vis spectrophotometer Agilent 8453 (Germany) was used in this study.

Total arsenic concentration, major cations, and other selected metals were analyzed using the inductively coupled plasma atomic emission spectroscopy (ICP-AES) Genesis system from Spectro Analytical Instruments (Kleve, Germany). The concentrations of major anions were obtained by ion chromatography (IC), 763 Compact, Metrohm (Herissau, Switzerland). ICP-AES Multielement standards, Ultraspec, Bruyn Spectroscopic Solutions (Johannesburg, South Africa), and multielement ion chromatography anions standard solution, Sigma- Aldrich (Johannesburg, South Africa), were used for calibration. A blank sample from the field was always analyzed the same way as the samples.

### Sediment Samples

Mineralogical composition of sediment samples was determined by X-ray diffraction (XRD). Analyses were performed using a Philips PW 3710 diffractometer with Ni-filtered Cu-K$\alpha$ radiation at a voltage of 40 kV and beam current of 30 mA. Samples were scanned between 3 and 75°2$\theta$ with a step size of 0.02°2$\theta$ and a counting time of 1 s per step. X'Pert HiScore Plus software (which allows semi-quantitative analysis using the reference intensity ratio (RIR) values) was used for quantification of the identified minerals (Snyder, 1992). The mineral composition was determined for powdered, non-oriented samples which had been prepared by gentle disaggregation with a mortar and pestle and passing through a 63 $\mu$m sieve before being packed into a powder holder.

### Data Analysis

A statistical analysis of the data (PCA) was conducted using Canoco v. 4.5 (ter Braak and Smilauer, 2002) and saturation indices were calculated using PHREEQCI Version 2 (Parkhurst and Appelo, 1999).

## Results

All the results are summarized in Table 1 and a few selected piezometers have been analyzed for arsenic using different analytical techniques in different laboratories in order to confirm the results (Table 2). In the HOORC laboratory, samples were analyzed using a graphite furnace (Varian GTA 110) as described in Huntsman-Mapila et al., 2006. In the CSIR laboratory (South Africa) the method of hydride generation coupled with inductively coupled plasma atomic emission spectroscopy (Hyd-ICP-AES) was used. Triplicate samples were also analyzed (Table 2) and the relative standard deviation (RSD) were found to be below 6. All field blank samples had arsenic values inferior to the detection limit (<0.5 $\mu$g/L).

### General Hydrochemistry Results

The EC was found to range between 92 and 18,120 $\mu$S/cm from the Boro River to the island center for the first sampling and 189 and 20,800 $\mu$S/cm for the second sampling. The conductivity and concentrations of solutes increase toward the center of the island with distance from the river (Fig. 2a). This observation is in agreement with reports by others (Heusser and Langer, 2004; Wolski et al., 2006; Bauer-Gottwein et al., 2007; McCarthy, 2006). The pH was 5.9 for the Boro River at both samplings and increased toward the island centers up to 8.7 (Fig. 2b). $HCO_3^-$ is the major anion in the island groundwater. The alkalinity in the center of the islands is up to 150–200 times higher than in the river water and groundwater from the edge of island. There is a noticeable increase in sulfate concentration from the edge of the island toward the center with concentration ranging from 0.159 to 595 mg/L. It should also be noted that $H_2S$ gas could be smelt while sampling some of the piezometers, in particular C3 and the piezometers in the island center. In this study, DOC ranges from 11 to 77 mg/L with a mean value of 29 mg/L from the edge of the island toward the center, in agreement with values reported by Mladenov et al. (2008) (Fig. 2c). Na

**Table 1** Results from field, anion, major cation, and trace metal analyses for the river water and island piezometers

| Sample | Distance (m) | pH | EC | Temp (°C) | DO | DOC | $CO_3^{2-}$ | $HCO_3^-$ | F | Cl | $NO_2^-$ | $NO_3^-$ | $PO_4^{3-}$ | $SO_4^{2-}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SWD | 0 | 5.87 | 92 | 27.7 | 0.56 | 8.6 | Nd | 80.2 | 0.124 | 0.891 | Nd | 0.036 | Nd | 0.12 |
| SWR | 0 | 5.85 | 189 | | 1.03 | 10.9 | Nd | 97.1 | 0.119 | 0.469 | Nd | 0.084 | Nd | 0.076 |
| C1D | 20 | 6.22 | 224 | 26.3 | 1.54 | 17.9 | Nd | 144.7 | 0.17 | 1.707 | Nd | 10.248 | Nd | 0.182 |
| C1R | 20 | 5.64 | 366 | | 0.24 | 14.4 | Nd | 260.5 | 0.186 | 1.325 | Nd | 11.425 | Nd | 0.286 |
| C2D | 21 | 6.31 | 219 | 24.4 | 1.7 | 15.9 | Nd | 158.2 | 0.155 | 1.179 | 7.487 | 0.691 | Nd | Nd |
| C2R | 21 | 5.8 | 392 | | 0.47 | 17.9 | Nd | 268.5 | 0.173 | 1.716 | 7.743 | 0.246 | 0.437 | 0.361 |
| C3D | 24 | 6.35 | 281 | 24 | 2.65 | 18.2 | Nd | 196 | 0.217 | 1.562 | 10.545 | 0.273 | Nd | 0.213 |

**Table 1** (continued)

| Sample | Distance (m) | pH | EC | Temp (°C) | DO | DOC | $CO_3^{2-}$ | $HCO_3^-$ | F | Cl | $NO_2^-$ | $NO_3^-$ | $PO_4^{3-}$ | $SO_4^{2-}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C3R | 24 | 5.91 | 383 | | 1.08 | 14.6 | Nd | 251.6 | 0.187 | 1.35 | 8.967 | 0.254 | Nd | 0.671 |
| C4D | 29 | 6.29 | 210 | 23.8 | 1.79 | 13.6 | Nd | 161 | 0.157 | 1.271 | 9.103 | 0.102 | 0.072 | 0.125 |
| C4R | 29 | 5.67 | 396 | | 0.8 | 16.1 | Nd | 183.8 | 0.172 | 0.703 | Nd | 0.091 | Nd | 0.159 |
| C5D | 44 | 6.42 | 340 | 23.7 | 1.27 | 15.4 | Nd | 215 | 0.237 | 0.715 | Nd | 23.545 | Nd | 0.79 |
| C5R | 44 | 6.29 | 455 | | 0.87 | 17.7 | Nd | 346.4 | 0.242 | 0.589 | Nd | 0.138 | Nd | 0.277 |
| C6D | 69 | 6.36 | 133 | 24.5 | 1.13 | 12.7 | Nd | 91.8 | 0.124 | 0.207 | Nd | 0.434 | 0.111 | 0.113 |
| C6R | 69 | 5.96 | 344 | | 0.88 | 10.8 | Nd | 224 | 0.182 | 6.259 | Nd | Nd | Nd | 2.09 |
| C7D | 104 | 6.56 | 663 | 25 | 2.09 | 16.5 | Nd | 391.6 | 0.298 | 0.589 | Nd | 0.08 | Nd | Nd |
| C7R | 104 | 6.3 | 702 | | 0.71 | 25.2 | Nd | 596.4 | 0.34 | 0.435 | Nd | Nd | Nd | 0.208 |
| C8D | 158 | 7.74 | 5569 | 28.9 | 1.75 | 28.9 | 140 | 4262 | Nd | 63.375 | Nd | Nd | Nd | 51.84 |
| C8R | 158 | 8.44 | 11150 | | 0.7 | 44.1 | 2375 | 28825 | Nd | 101.19 | Nd | Nd | Nd | 86.39 |
| C9D | 168 | 8.48 | 10530 | 32.4 | 5.08 | 33.4 | 476 | 8319 | 0.99 | 54.525 | Nd | Nd | Nd | 59.54 |
| C9R | 168 | 7.84 | 9770 | | 2.9 | 23.7 | 320 | 12073 | 0.705 | 42.33 | Nd | Nd | Nd | 42.15 |
| C10D | 212 | 8.51 | 17480 | 27.2 | 0.77 | 75 | 1161 | 15495 | 3.21 | 68.52 | Nd | Nd | Nd | 204.6 |
| C10R | 212 | 8.65 | 20100 | | 0.94 | 77.1 | 1969 | 26267 | 3.135 | 73.395 | Nd | Nd | Nd | 205.9 |
| C11D | 246 | 8.73 | 18120 | 28.6 | 1.65 | 65.4 | 1198 | 15367 | 2.835 | 458.355 | Nd | Nd | Nd | 606.5 |
| C11R | 246 | 8.66 | 20800 | | 0.8 | 73.6 | 1832 | 25357 | 2.835 | 445.29 | Nd | Nd | Nd | 595.1 |

| **Sample** | **Na** | **K** | **Ca** | **Mg** | **Fe** | **Mn** | **Al** | **As** | **Li** | **Co** | **Ni** | **Pb** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SWD | 5.8 | 5.96 | 7.95 | 2.4 | 0.06 | 0.013 | 1.001 | 0.001 | 0.001 | 0.001 | Nd | 0.004 |
| SWR | 13.8 | 9.5 | 7.8 | 2 | 0.049 | 0.011 | 0.025 | 0.002 | 0.001 | Nd | 0.003 | 0.023 |
| C1D | 7.8 | 7.06 | 19.7 | 5.9 | 2.28 | 0.42 | 0.006 | 0.002 | 0.003 | Nd | 0.001 | 0.008 |
| C1R | 6.7 | 5.7 | 27.4 | 7.2 | 3 | 0.58 | 0.037 | 0.002 | 0.003 | 0.002 | 0.007 | 0.018 |
| C2D | 18.3 | 11.6 | 20.4 | 5.8 | 0.52 | 0.37 | Nd | Nd | 0.004 | 0.001 | Nd | Nd |
| C2R | 49.7 | 15 | 27.7 | 6.3 | 1.8 | 0.52 | 0.045 | 0.008 | 0.003 | 0.004 | 0.007 | 0.009 |
| C3D | 5.8 | 8.36 | 26.5 | 6.1 | 2.49 | 1.04 | 0.02 | Nd | 0.004 | 0.003 | Nd | Nd |
| C3R | 7.9 | 6.4 | 37.9 | 9.6 | 1.3 | 0.96 | 0.02 | 0.003 | 0.005 | 0.005 | 0.008 | 0.018 |
| C4D | 4.81 | 7.25 | 17.7 | 4.6 | 0.95 | 0.61 | 0.675 | Nd | 0.004 | 0.002 | Nd | 0.001 |
| C4R | 39.1 | 7.6 | 20.9 | 5.4 | 3.4 | 0.57 | 0.028 | 0.009 | 0.003 | 0.002 | 0.007 | Nd |
| C5D | 9.82 | 7.44 | 35 | 6.3 | 1.23 | 0.76 | 0.011 | Nd | 0.003 | 0.002 | Nd | Nd |
| C5R | 41.1 | 8.8 | 52.2 | 9.6 | 0.076 | 0.96 | 0.16 | 0.011 | 0.004 | 0.004 | 0.005 | 0.005 |
| C6D | 21.8 | 7.03 | 13.3 | 2.8 | 0.94 | 0.25 | 0.021 | Nd | 0.002 | Nd | Nd | 0.007 |
| C6R | 93.9 | 9.5 | 25.5 | 7.2 | 0.44 | 0.42 | 0.04 | 0.014 | 0.003 | 0.005 | 0.004 | 0.014 |
| C7D | 845.8 | 7.6 | 9.52 | 9.2 | 1.13 | 0.64 | 0.06 | 0.004 | 0.016 | Nd | 0.002 | Nd |
| C7R | 82.8 | 12.4 | 84.6 | 11.1 | 8.2 | 0.64 | 0.017 | 0.021 | 0.016 | 0.009 | 0.011 | 0.011 |
| C8D | 1894.8 | 825.5 | 18.87 | 53.9 | 0.03 | 0.16 | 0.037 | 0.279 | 0.088 | 0.003 | Nd | 0.179 |
| C8R | 3949 | 1365 | 14.1 | 46.8 | 0.23 | 0.05 | 0.126 | 0.651 | 0.106 | 0.04 | Nd | 0.113 |
| C9D | 2822 | 1040 | 13.8 | 23.6 | 0.05 | 0.09 | 0.115 | 0.371 | 0.129 | 0.003 | Nd | 0.033 |
| C9R | 3139 | 452.9 | 26.2 | 26.2 | 0.05 | 0.3 | 0.076 | 0.251 | 0.095 | 0.024 | Nd | 0.152 |
| C10D | 4202 | 278 | 3.3 | 3 | 0.14 | 0.08 | 0.011 | 1.818 | 0.094 | 0.009 | Nd | 0.035 |
| C10R | 7795 | 305.9 | 3 | 2.5 | 0.17 | 0.09 | 0.063 | 2.3 | 0.1 | 0.024 | Nd | 0.072 |
| C11D | 4292 | 253.6 | 2.46 | 3.7 | 0.07 | 0.02 | 0.093 | 2.123 | 0.099 | 0.003 | 0.001 | Nd |
| C11R | 8190 | 286.9 | 2.6 | 3.2 | 0.11 | 0.06 | 0.092 | 3.2 | 0.119 | 0.022 | Nd | 0.046 |

All RSD (%) < 10

Concentration in mg/L and EC in µs/cm; D, first sampling; R, second sampling; SW, Boro surface water; C1–C11, underground water; Nd, not detected; DO, dissolved oxygen; DOC, dissolved organic carbon

**Table 2** Arsenic results from different laboratories and arsenic triplicate samples

| Date sampled | Sample | Method used | Lab | Arsenic (mg/L) |
|---|---|---|---|---|
| (a) Different laboratory analysis | | | | |
| Dec 05 | SW | GTA | HOORC | 0.0015 |
| Dec 05 | SW | Hyd-ICP-AES | CSIR | <0.002 |
| Dec 05 | C8 | GTA | HOORC | 0.141 |
| Dec 05 | C8 | Hyd-ICP-AES | CSIR | 0.100 |
| Dec 05 | C10 | GTA | HOORC | 2.730 |
| Dec 05 | C10 | Hyd-ICP-AES | CSIR | 2.300 |
| Dec 05 | C11 | GTA | HOORC | 2.770 |
| Dec 05 | C11 | Hyd-ICP-AES | CSIR | 2.500 |
| Jan 08 | SW | ICP-AES | Wits Univ | 0.001 |
| Jan 08 | SW | Hyd-ICP-AES | CSIR | <0.002 |
| Jan 08 | C8 | ICP-AES | Wits Univ | 0.279 |
| Jan 08 | C8 | Hyd-ICP-AES | CSIR | 0.124 |
| Jan 08 | C9 | ICP-AES | Wits Univ | 0.371 |
| Jan 08 | C9 | Hyd-ICP-AES | CSIR | 0.335 |
| Jan 08 | C10 | ICP-AES | Wits Univ | 1.820 |
| Jan 08 | C10 | Hyd-ICP-AES | CSIR | 1.610 |
| Jan 08 | C11 | ICP-AES | Wits Univ | 2.120 |
| Jan 08 | C11 | Hyd-ICP-AES | CSIR | 1.510 |
| (b) Triplicate sample | | | | |
| Mar 08 | SW | ICP-AES | Wits Univ | 0.002 |
| Mar 08 | SW | ICP-AES | Wits Univ | 0.002 |
| Mar 08 | SW | ICP-AES | Wits Univ | 0.002 |
| Mar 08 | C8 | ICP-AES | Wits Univ | 0.661 |
| Mar 08 | C8 | ICP-AES | Wits Univ | 0.641 |
| Mar 08 | C8 | ICP-AES | Wits Univ | 0.652 |
| Mar 08 | C10 | ICP-AES | Wits Univ | 2.281 |
| Mar 08 | C10 | ICP-AES | Wits Univ | 2.333 |
| Mar 08 | C10 | ICP-AES | Wits Univ | 2.290 |
| Mar 08 | C11 | ICP-AES | Wits Univ | 3.211 |
| Mar 08 | C11 | ICP-AES | Wits Univ | 3.170 |
| Mar 08 | C11 | ICP-AES | Wits Univ | 3.280 |

RSD (%) < 6.2

SW, Boro surface water; C8–C11, groundwater sample

and Cl accumulate along the island transect with the concentrations of Cl approximately 500–1000 times higher in the middle of the island than in the river water. A similar pattern is found for Na with concentration values of up to 4200–8200 mg/L in the center of the ORC island and only 5–14 mg/L in the river water and groundwater at the edge of island. K increases along the island transect up to C9 and then starts to decrease.

Arsenic follows the same trend (Fig. 2) of increasing toward the island center (Fig. 2d). Its concentration ranges between 0.002 and 3.200 mg/L (mean 0.539 mg/L) for the first sampling (D) and between 0.001 and 2.123 (mean 0.383 mg/L) for the second sampling (R). This increase is noticed especially from the sample C8 to C11. These samples are also characterized by a higher pH ranging between 7.7 and 8.7. This positive correlation was also found by Huntsman-Mapila et al. (2006).

A Piper diagram was constructed to show the major water types for the surface and groundwater samples using the data from the second sampling (R; Fig. 3). The surface water sample has the symbol of an open square; samples C1–C7 are represented with an open

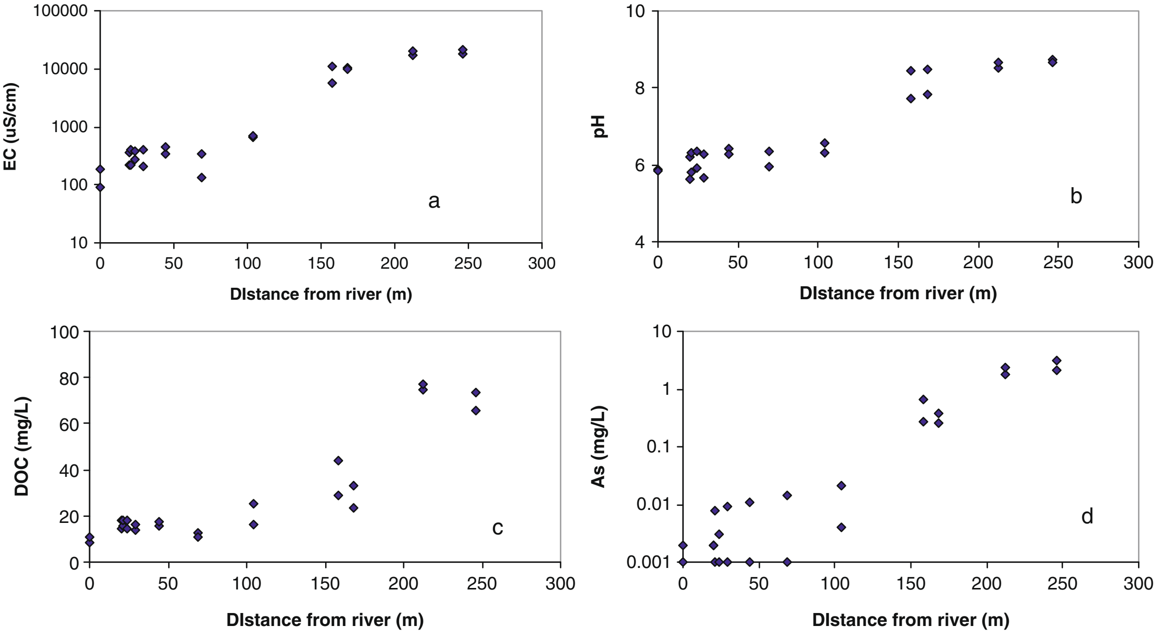

**Fig. 2** Profiles of conductivity (**a**), pH (**b**), DOC (**c**), and As (**d**) along the transect with distance from the river. In order to maintain figure clarity, conductivity and As are shown using a log scale

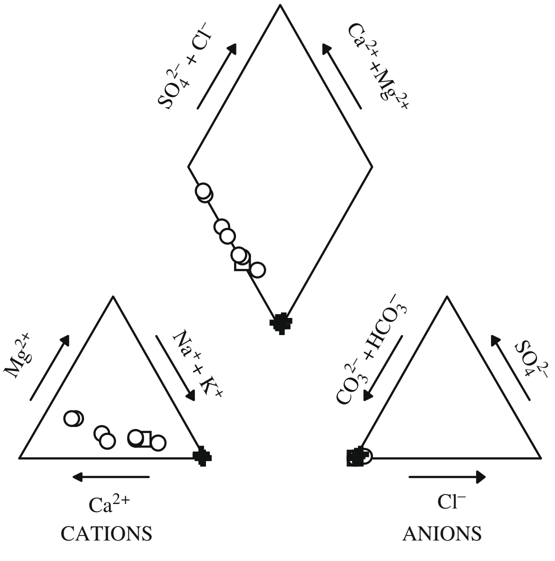

**Fig. 3** Piper diagram showing the Okavango Delta surface water (*open square*), island fringe groundwater (*open circle*), and island center groundwater (*cross*)

circle while samples C8–C11 are represented with the symbol of a cross. It is clear that all samples are carbonate/bicarbonate-type water with the main variation occurring in the cation composition. Samples from the island center are sodium/potassium-type waters while some of the island fringe piezometers are predominantly calcium-rich water.

A PCA was done on the combined data set (both samplings) where all data were centered and standardized to allow interpretation in terms of correlation coefficients and to take account of the different units. The center of the PCA biplot (Fig. 4) where all the arrows stem from is the mean of each environmental variable. The direction of the arrow, therefore, represents the increasing concentration of that variable and the angle between variables, and between variables and the axes 1 and 2, can be interpreted in terms of correlation coefficients where the smaller the angle, the higher the correlation. Axis 1 is therefore being driven by a suite of variables, including alkalinity, EC, Na, pH, Ca, and Mn and axis 2 is more associated with DO and Mg. The smaller the angle between variables, the closer the correlation is to 1. Figure 4 shows that the two alkalinity variables are very highly correlated, and they are also highly correlated with Na, pH, EC, and other variables. Arsenic is most highly correlated with not only halogens Cl and F, but also $SO_4$. It is next most closely correlated with DOC and next with EC and Na. Note that these variables are strongly negatively correlated with Ca, Mn, Fe, Ni, and Al (due to angle between vectors approaching 180°). The results

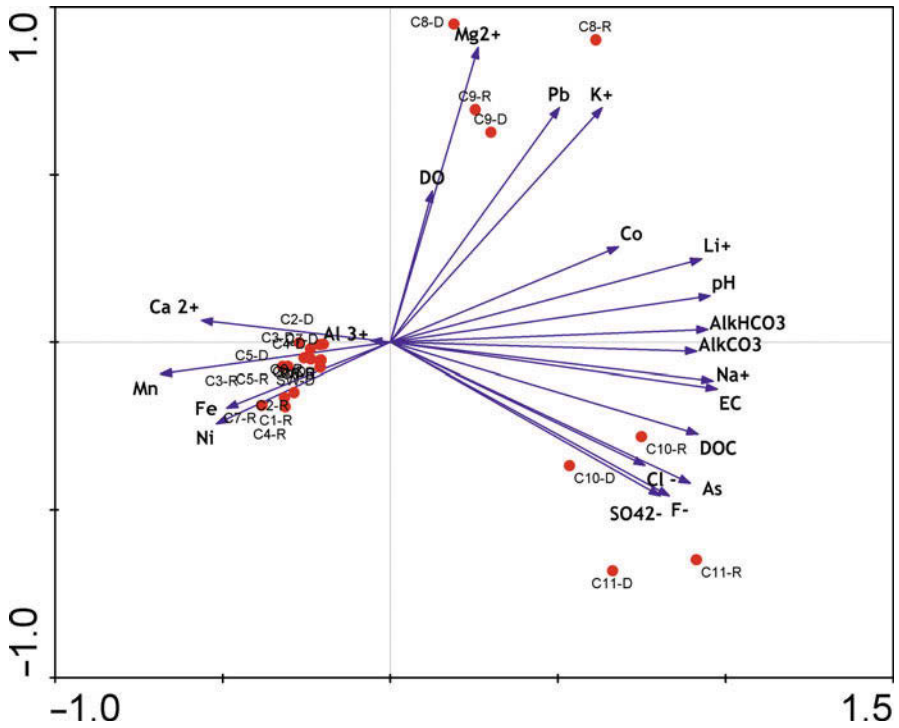

**Fig. 4** PCA biplot of both data sets (D and R)

are essentially similar between the two samplings with C10 and C11 both containing high amounts of As, Cl, $SO_4^{2-}$ and samples C8 and C9 containing relatively high concentrations of Mg, Pb, and K.

## Sediment Mineralogy

Results of the XRD analyses on sediment samples from C9 and C10 are presented in Table 3. Quartz is the dominant mineral in each sample, with calcite and kaolinite present in significant percentages and trace amounts of smectite which is present in quantities too small to identify/quantify. In the C9 samples, calcite is generally present in quantities below 7%; however, at 4 and 5 m, it is present in more significant amounts (30 and 22%), respectively. In the C10 samples, calcite is similarly present in quantities below 8% for most of the samples. Mg-rich calcite is noted at two levels, 1 and 4 m. In the C9 samples, kaolinite is generally present in quantities below 16%; however, in the samples taken at 3 and 3.5 m it accounts for 26 and 45% of the samples, respectively. In the C10 samples, kaolinite is generally present in quantities below 18%; however, in the samples from 3 and 5 m it is present in quantities of 57 and 35%, respectively.

The composition of water samples C11R and C6R was selected to run on PHREEQCI Version 2 (Parkhurst and Appelo, 1999) using the wateq4f database file to include arsenic values. Both samples are saturated with respect to a number of Al and Fe oxides and hydroxides (Table 4). The modeling revealed that the island groundwater is undersaturated with respect to As minerals. It is interesting to note that despite decreasing K values at the center of the island, the model did not suggest precipitation of any K-containing minerals. Since carbonate minerals are important components of the Okavango sediments, groundwater chemistry is strongly controlled by carbonate reactions. C11R groundwater is saturated with respect to aragonite, calcite, dolomite, huntite, magnesite, and rhodochrosite. C11R is undersaturated with respect to trona, as is C6R, although precipitates of trona do form on the surface of the island center at the end of the rainy season.

**Table 3** Results from XRD analyses on sediment samples from piezometers C9 and C10

| Borehole | Depth (m) | Quartz | Calcite | Kaolinite | Mg calcite | Smectite |
|---|---|---|---|---|---|---|
| C9 | 2 | 87 | 2 | 10 | | x |
| | 3 | 66 | 7 | 26 | | x |
| | 3.5 | 54 | 1 | 45 | | |
| | 4 | 53 | 30 | 16 | | x |
| | 5 | 64 | 22 | 13 | | x |
| | 6 | 85 | 3 | 11 | | x |
| C10 | 1 | 72 | 8 | 13 | 7 | |
| | 2 | 80 | 8 | 12 | | |
| | 3 | 40 | 3 | 57 | | |
| | 4 | 65 | | 15 | 19 | x |
| | 5 | 57 | 8 | 35 | | |
| | 6 | 81 | | 18 | | x |

x, trace amounts

**Table 4** Selected saturation indices calculated from PHREEQC I version 2

| Phase | SI | log IAP | log KT | Formula |
|---|---|---|---|---|
| **Sample C11R** | | | | |
| Aragonite | 0.68 | −7.66 | −8.34 | $CaCO_3$ |
| Arsenolite | −36.06 | −37.44 | −1.38 | $As_2O_3$ |
| $As_2O_5$(cr) | −33.74 | −25.52 | 8.23 | $As_2O_5$ |
| As_native | −44.16 | −56.69 | −12.53 | As |
| Calcite | 0.82 | −7.66 | −8.48 | $CaCO_3$ |
| Claudetite | −36.10 | −37.44 | −1.34 | $As_2O_3$ |
| Diaspore | 1.55 | 8.43 | 6.88 | AlOOH |
| Dolomite | 2.21 | −14.88 | 17.09 | $CaMg(CO_3)_2$ |
| Dolomite(d) | 1.66 | −14.88 | −16.54 | $CaMg(CO_3)_2$ |
| $Fe(OH)_{2.7}Cl_{0.3}$ | 6.52 | 3.48 | −3.04 | $Fe(OH)_{2.7}Cl_{0.3}$ |
| $Fe(OH)_3$(a) | 1.80 | 6.69 | 4.89 | $Fe(OH)_3$ |
| $Fe_3(OH)_8$ | 0.22 | 20.44 | 20.22 | $Fe_3(OH)_8$ |
| Gibbsite | 0.31 | 8.42 | 8.11 | $Al(OH)_3$ |
| Goethite | 7.70 | 6.70 | −1.00 | FeOOH |
| Hematite | 17.41 | 13.40 | −4.01 | $Fe_2O_3$ |
| Huntite 4 | 0.64 | −29.33 | −29.97 | $CaMg_3(CO_3)$ |
| Maghemite | 7.02 | 13.40 | 6.39 | $Fe_2O_3$ |
| Magnesite | 0.81 | −7.22 | −8.03 | $MgCO_3$ |
| Magnetite | 16.73 | 20.47 | 3.74 | $Fe_3O_4$ |
| $Mn_3(AsO_4)_2{:}8H_2O$ | −12.92 | −41.63 | −28.71 | $Mn_3(AsO_4)_2{:}8H_2O$ |
| Rhodochrosite | 0.27 | −10.86 | −11.13 | $MnCO_3$ |
| Scorodite | −6.93 | −27.18 | −20.25 | $FeAsO_4{:}2H_2O$ |
| Trona | −4.05 | −4.85 | −0.80 | $NaHCO_3{:}Na_2CO_3{:}2H_2O$ |
| **Sample C6R** | | | | |
| Aragonite | −1.85 | −10.19 | −8.34 | $CaCO_3$ |
| Arsenolite | −20.68 | −22.06 | −1.38 | $As_2O_3$ |
| $As_2O_5$(cr) | −29.14 | −20.92 | 8.23 | $As_2O_5$ |
| As_native | −28.38 | −40.91 | −12.53 | As |

**Table 4** (continued)

| Phase | SI | log IAP | log KT | Formula |
|---|---|---|---|---|
| Boehmite | 0.79 | 9.37 | 8.58 | AlOOH |
| $Ca_3(AsO_4)_2$:4w | −18.52 | −37.43 | −18.91 | $Ca_3(AsO_4)_2:4H_2O$ |
| Calcite | −1.71 | −10.19 | −8.48 | $CaCO_3$ |
| Claudetite | −20.72 | −22.06 | −1.34 | $As_2O_3$ |
| Diaspore | 2.49 | 9.37 | 6.88 | AlOOH |
| Dolomite | −3.62 | −20.71 | −17.09 | $CaMg(CO_3)_2$ |
| Dolomite(d) | −4.17 | −20.71 | −16.54 | $CaMg(CO_3)_2$ |
| $Fe(OH)_{2.7}Cl_{0.3}$ | 3.62 | 0.58 | −3.04 | $Fe(OH)_{2.7}Cl_{0.3}$ |
| $Fe(OH)_3$(a) | −1.39 | 3.51 | 4.89 | $Fe(OH)_3$ |
| $Fe_3(OH)_8$ | −6.65 | 13.58 | 20.22 | $Fe_3(OH)_8$ |
| Gibbsite | 1.26 | 9.37 | 8.11 | $Al(OH)_3$ |
| Goethite | 4.51 | 3.51 | −1.00 | FeOOH |
| Hematite | 11.02 | 7.01 | −4.01 | $Fe_2O_3$ |
| Huntite | −11.78 | −41.75 | −29.97 | $CaMg_3(CO_3)_4$ |
| Maghemite | 0.63 | 7.01 | 6.39 | $Fe_2O_3$ |
| Magnesite | −2.49 | −10.52 | −8.03 | $MgCO_3$ |
| Magnetite | 9.84 | 13.58 | 3.74 | $Fe_3O_4$ |
| $Mn_3(AsO_4)_2:8H_2O$ | −14.73 | −43.44 | −28.71 | $Mn_3(AsO_4)_2:8H_2O$ |
| $Ni_3(AsO_4)_2:8H_2O$ | −24.78 | −50.29 | −25.51 | $Ni_3(AsO_4)_2:8H_2O$ |
| Rhodochrosite | −1.06 | −12.19 | −11.13 | $MnCO_3$ |
| Rhodochrosite(d) | −1.80 | −12.19 | −10.39 | $MnCO_3$ |
| Scorodite | −7.81 | −28.06 | −20.25 | $FeAsO_4:2H_2O$ |
| Trona | −15.79 | −16.59 | −0.80 | $NaHCO_3:Na_2CO_3:2H_2O$ |

## Discussion

Organic species have been shown to contribute significantly to the aqueous and mobile arsenic pool (Bauer et al., 2008; Huang and Matzner, 2006, 2007a, b). DOC is used to estimate organic matter content such as humic acid content. DOC was found to play a role in the chemistry of groundwater of Okavango (Huntsman-Mapila et al., 2006; Mladenov et al., 2008). In this study, DOC ranges from 11 to 77 mg/L with a mean value of 29 mg/L from the edge of the island toward the center. As is positively correlated to sulfate. A positive correlation between As and sulfate is often observed in acid mine drainage with a low pH and low alkalinity. It is suggested that the observed correlation between As and sulfate in this data set is an effect of concentration by evapo-transpiration on the two parameters.

Huntsman-Mapila et al. (2006) reported a relatively strong correlation between As and percent fines in sediment samples from the delta and to a lesser extent between As and Fe in the sediment samples. Once Fe oxide reduction starts in the aquifer, arsenic is either desorbed from the surface of the dissolving Fe oxide or it is released from the mineral structure itself (Nickson et al., 1998, 2000; McArthur et al., 2001; Dowling et al., 2002; Harvey et al., 2002; Swartz et al., 2004). The idea of arsenic mobilization by displacement from sediment surfaces by $HCO_3^-$ generated through the dissolution of carbonate and the reduction of Fe oxides has been also proposed (Appelo et al., 2002; Anawar et al., 2003; Postma et al., 2007). Results from PHREEQC calculations indicate that along the island transect, the groundwater is saturated in a number of Fe and Al oxides and hydroxides (Table 3) and therefore precipitation of these minerals is thermodynamically predicted to occur. Given the correlation between As and EC and Cl (a conservative ion) and the high As concentration at the island center, it is suggested that evapo-transpiration is the dominant process governing the elevated As. However, reductive dissolution of oxides and hydroxides containing Fe may be the initial step for the release of As into groundwater.

DOC plays an important role with regard to understanding redox processes and evaluating the influence of DOM on groundwater geochemistry in the Okavango Delta (Mladenov et al., 2008). The DOM may have an important influence in metal–DOM interactions, electron shuttling, sorption, and/or coagulation. The reducing conditions in the groundwater of Okavango island interiors may be linked to microbial reduction of metals using the DOM as substrate and fulvic acids as electron shuttles (Mladenov et al., 2008).

The results from this work suggest that the observed As enrichments seem to be the result of a complex interplay between (1) concentration by evaporation/transpiration; (2) reductive dissolution of Fe oxyhydroxides, masked by reprecipitation; and (3) competitive interaction between $HCO_3^-$ and As for the same sorption sites as pH increases.

## Island Groundwater for Water Supply

The arsenic study conducted in 2003 (Huntsman-Mapila et al., 2006) on boreholes in the lower delta was significant as the boreholes were being installed in order to enhance the water supply to Maun and neighboring villages. Of 20 boreholes, 6 were found to have values exceeding 10 μg/L with the highest sample recording 116.6 μg/L As. The samples analyzed in this study were taken from piezometers installed for research purposes and are not used for drinking water supply. This data set suggests that elevated arsenic is associated with very saline water which would not be potable due to the high salt content.

## Conclusion

The elevated arsenic concentration in the Okavango groundwater is attributed to a natural source (Huntsman-Mapila et al., 2006) but further work is required to determine the provenance of arsenic in the Okavango Delta system. An increase in arsenic concentration in shallow groundwater was found along an island transect over a distance of 250 m. Arsenic was positively correlated to conservative elements (Na and Cl), electrical conductivity, alkalinity, DOC, pH, potassium, and sulfate and negatively correlated to nitrate.

From this study, it is proposed that the enrichment of As in the island groundwater of the Okavango Delta is a result of a complex interplay between (1) concentration by evaporation/transpiration; (2) reductive dissolution of Fe oxyhydroxides, masked by reprecipitation; and (3) competitive interaction between $HCO_3^-$ and As for the same sorption sites as pH increases. The predominant process controlling the very elevated levels of arsenic in the island center groundwater is probably the effect of the evapotranspiration. However, reductive dissolution of oxide and hydroxide of minerals containing Fe and Mn is proposed as the initial step for the release of arsenic from the sediment to the groundwater although there was no correlation of arsenic with iron or manganese due to reprecipitation of oxides of these metals.

DOC has important implications for the Okavango Delta in regard to understanding redox processes and evaluating the influence of DOM and humic substances on groundwater geochemistry (Mladenov et al., 2008; Huntsman- Mapila et al., 2006). Further investigations are needed to understand the redox processes that may be occurring in the Okavango Delta groundwater and the associated DOM–iron–arsenic interactions in groundwater of this recharge wetland. In addition, the solid phase should also be characterized to enhance our understanding of As mobilization.

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# Sustainability of Groundwater Resources in the North China Plain

Jie Liu, Guoliang Cao, and Chunmiao Zheng

**Abstract**

The North China Plain (NCP) has one of the most depleted aquifers in the world due to over-pumping to meet the needs of fast economic growth and intensive irrigation. With limited and temporally uneven precipitation, nearly 70% of the total water supply in the NCP comes from groundwater to maintain its food basket role in China and to support the fast economic development and population growth. This causes continuing water table declines and results in adverse consequences such as land subsidence, sea water intrusion, drying up of rivers and wetlands, and deterioration of the ecosystem. This chapter first provides an overview of general water resource information for the NCP and then discusses the methodologies and tools that can be used to address the questions pertinent to sustainability of groundwater resources. A regional groundwater flow model covering the entire NCP is presented to quantify the groundwater flow system and overall flow budgets. The groundwater flow model will be a useful tool for future impact assessment of a wide range of water resource management options for the NCP. The findings and insights from this study will have important implications for other parts of the world under similar hydrogeologic conditions.

**Keywords**

North China Plain • NCP • Groundwater modeling • Sustainable water management

## Introduction

### North China Plain

The North China Plain (NCP), also referred as the Huang–Huai–Hai Plain, is a common name for the plain areas of three major river basins in northern China, namely, the Huang (Yellow), Huai, and Hai River Basins. It covers an area of 320,000 km$^2$ with a total population in excess of 200 million and is the largest alluvial plain of eastern Asia (Kendy et al.,

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J.A.A. Jones (ed.), *Sustaining Groundwater Resources*, International Year of Planet Earth,
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2003). From the viewpoint of water resource management and economic importance, a narrower definition of the NCP is more commonly used – the region bordering on the north by the Yan Mountains, on the west by the Taihang Mountains, to the south by the Yellow River, and to the northeast by the Bohai Gulf (Fig. 1). This region includes all the plains of Hebei Province, Beijing Municipality, Tianjin Municipality, and the northern parts of the plains in Shandong and Henan Provinces. The total area of this narrowly defined NCP is 136,000 km$^2$ with a population around 111 million. In the subsequent discussions of this chapter, the NCP refers to the narrower definition described above. It was in the NCP that the ancient Chinese civilization originated as a society developed from agriculture and has since flourished for more than 4,000 years (Postel, 1999). Till today, the NCP remains the predominant national center of wheat and maize production and an extremely important economic, political, and cultural region of China, producing 10% of the nation's foodstuff and 12% of the nation's GDP.

In the NCP, water is the most vital and limiting resource (Kendy et al., 2003). On average, the annual precipitation is around 500 mm, which accounts for only 335 m$^3$ of renewable water resources per capita per year (China Geological Survey, 2005). This is only one-third the threshold value of 1,000 m$^3$ per capita adopted in the widely used Falkenmark indicator or "water stress index" (Falkenmark et al., 1989), denoting a region experiencing water scarcity. In addition, precipitation fluctuates widely from one year to the next, with 50–80% of the total annual precipitation concentrated in the summer monsoon months (July to September). Finite clean surface water is diverted into cities for municipal use, leaving industries and agriculture to compete over a diminishing groundwater resource. Average annual groundwater pumping from the shallow aquifer shows an obvious increasing trend (Fig. 2), and in the year 2000, approximately 74% of the annual water supply comes from groundwater pumping. Due to surface water interception by reservoirs and groundwater over-pumping, natural streams and rivers have almost completely ceased,

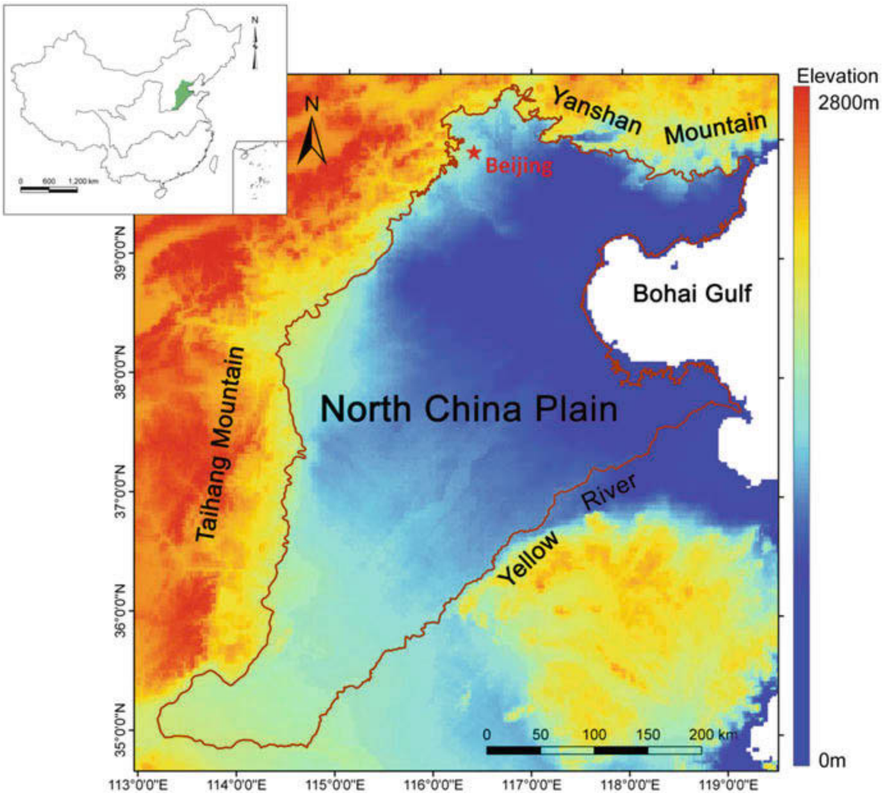

**Fig. 1** Location of the North China Plain

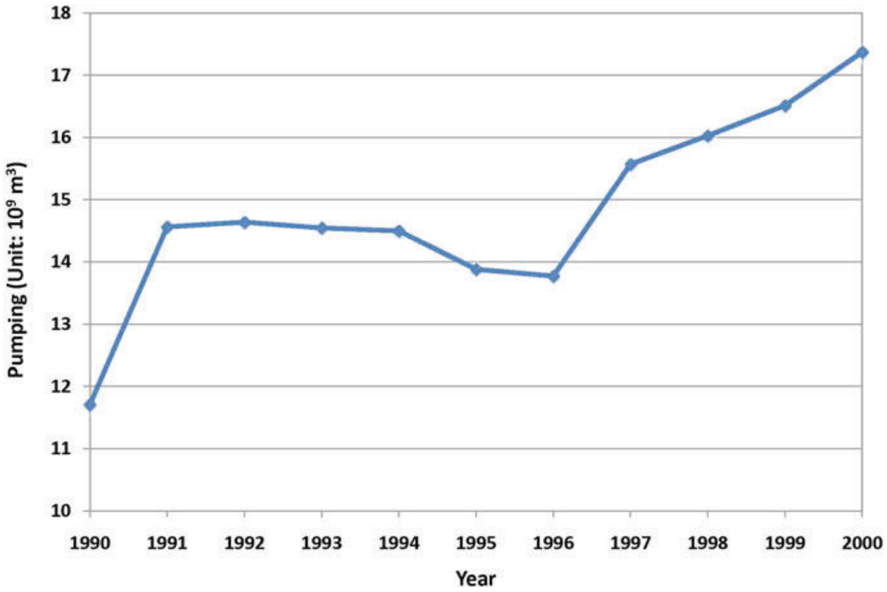

**Fig. 2** Annual groundwater pumping from the shallow aquifer of the NCP from 1990 to 2000

wetland areas have been shrinking, groundwater levels are declining steadily, salt water is intruding into what were previously fresh water aquifers, and in many places, the land surface is subsiding (Kendy et al., 2003).

The NCP aquifer system has become one of the most overexploited in the world (Ministry of Water Resources of PRC et al., 2001; Kendy et al., 2003; Liu et al., 2008). In 2007, American newspaper *New York Times* reported on the water scarcity problem in the NCP and stated that the aquifers below the NCP may be drained within 30 years (http://www.nytimes.com/interactive/2007/09/28/world/asia/choking_on_growth_2.html). The water scarcity problem in the NCP has drawn great attention from all over the world, because many areas in other countries are experiencing the same problem. For example, the Ogallala Aquifer in the USA, the Northern Sahara Aquifer System, the Karoo Aquifers in South Africa, and the aquifers in Yemen, India, and Mexico are all being drained to dangerously low levels. The study of the sustainability of groundwater resources in the NCP will not only help identify ways for alleviating water scarcity of this specific region but also provide a good case study for similarly water stressed regions in other parts of the world.

## Purpose and Organization

The direct motivation for this research arises from the urgent needs to address the serious water and environmental stresses caused by extensive over-pumping of groundwater and competitive water uses in the NCP. The purpose is to better understand the water scarcity problem in the NCP and use case study to illustrate how the sustainability or the lack thereof can be quantified and addressed through numerical modeling. This study of the NCP is also intended to provide an illustrative example for similar regions, such as northwest India, parts of Pakistan, western USA, and the Middle East, which serve as the bread baskets and rice bowls for local economies but are all experiencing over-pumping of groundwater.

A clear understanding of the aquifer system and the water resource situation is a prerequisite for sustainable development and management of groundwater resources. Therefore, the hydrogeology and water resources of the NCP will first be introduced. Then the methodologies and tools that can be used to address sustainability and sustainable groundwater development and management will be reviewed. Finally, the concepts and techniques of groundwater sustainability analysis are illustrated through the development of a regional groundwater flow model for the NCP.

## Hydrogeology and Water Resources

### Climate

The NCP is situated in the warm temperate, semi-arid, monsoon climatic zone of Eurasia, characterized by cold, dry winters (December to March) and hot, humid summers (July to September). The average annual precipitation is 500–600 mm, with 50–80% of the total concentrated in the summer monsoon months (July to September). Precipitation fluctuates widely from one year to the next, less than 400 mm in dry years and more than 800 mm in wet years (Fig. 3). Spatially, the coastal area has relatively more precipitation than the average (600–650 mm), while the central plain has an annual average precipitation of less than 500 mm, because of the rain shadow effect of mountains and the subsidence of airflow from the north (Zhang et al., 2006).

The average annual temperature is 10–15°C, with the lowest temperature of –1.8 to 1°C appearing in January and the highest temperature of 26–32°C in July. The annual total sunshine hours are around 2,400–3,100 h and the frostless period is about 200 days. The annual evaporation from water surface is 900–1,400 mm, being steady in January and February, starting to increase in March, accelerating from April to May, reaching the maximum from June to September, and decreasing after October. Evaporation increases with temperature and decreases with increasing latitude. This unevenly distributed precipitation and evaporation, spatially and temporally, have a direct impact on the distribution of groundwater resources and saline lands (Zhang et al., 2006).

### Surface Water and Aquifer System

Besides the three major river systems – the Yellow River, the Hai River, and the Luan River – there are nearly 60 small rivers like the Tuhai and the Majia River in the NCP. However, with the decrease of precipitation and the interception by reservoirs upstream, most of the river channels in the NCP are perennially drying up or only have short-term flows during the flooding season.

The Yellow River is the second largest river in China, located along the southern boundary of the NCP. The length of the Yellow River within the NCP is 755 km, among which about 345 km in Henan Province and about 410 km in Shandong Province. The Yellow River is well known for its high sediment content and the downstream is usually called the "aboveground river," with the elevation of the river

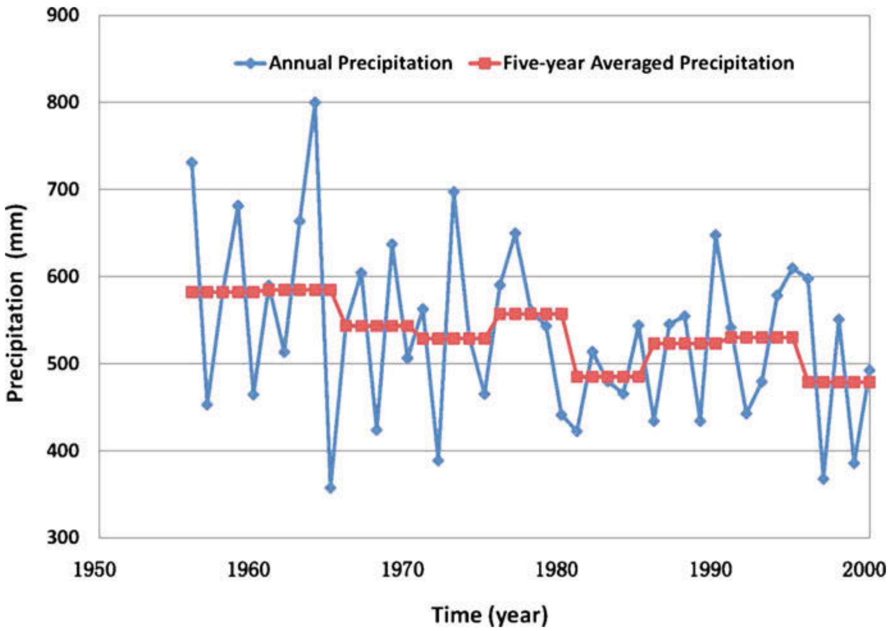

**Fig. 3** Precipitation variations from 1956 to 2000 on the Hai River Basin including NCP. (Hai River Commission, 2000)

bed 3–7 m higher than the surrounding ground surface. It constitutes the divide of both surface water and groundwater watersheds. The runoff of the Yellow River is uneven within a year, mostly concentrated in the flooding season. Based on the data from 1980 to 1989 at Huayuankou Station, the annual average water level of the Yellow River is 92.12 m. The "aboveground" characteristic of the Yellow River provides favorable condition for laterally recharging groundwater (Zhang et al., 2006).

The aquifer system in the NCP is composed of porous Quaternary formations (Fig. 4). According to the Institute of Hydrogeology and Environmental Geology (IHEG), Chinese Academy of Geological Sciences (CAGS), the deposits can be divided into four major aquifer layers (I–IV in Fig. 4) with the thickness of each between 20 and 350 m. All aquifer units are composed of permeable sand and gravel layers interbedded with fine sand and silt aquitard layers. The first aquifer unit from the top is unconfined, while the other three are confined but may convert to unconfined when significant drawdown occurs. The top two layers are traditionally called "shallow aquifer" and the bottom two are referred to as "deep aquifer". Hydraulically they are connected and pumping wells have been extracting groundwater from both of them. Porous Quaternary deposits provide favorable conditions for vertical groundwater recharge, and the infiltration from precipitation constitutes the most important groundwater recharge source in the study area. The piedmont area of the Taihang Mountains, which lies along the western boundary of the study area, is an important source of lateral groundwater recharge. According to the "*Water Resources Bulletin*" released in 2006 by the Ministry of Water Resources of China, the available groundwater resource in the NCP in the year of 2006 is 15.7 billion m$^3$.

## Water Resources in the NCP

The Ministry of Water Resources of China releases the "*Water Resources Bulletin*" of major river basins in China every year. The water resources information of the NCP was extracted from the latest available Water Resources Bulletin (2006) for the Hai River Basin, which includes both the plain areas discussed in this study and the mountain terrains. The total water

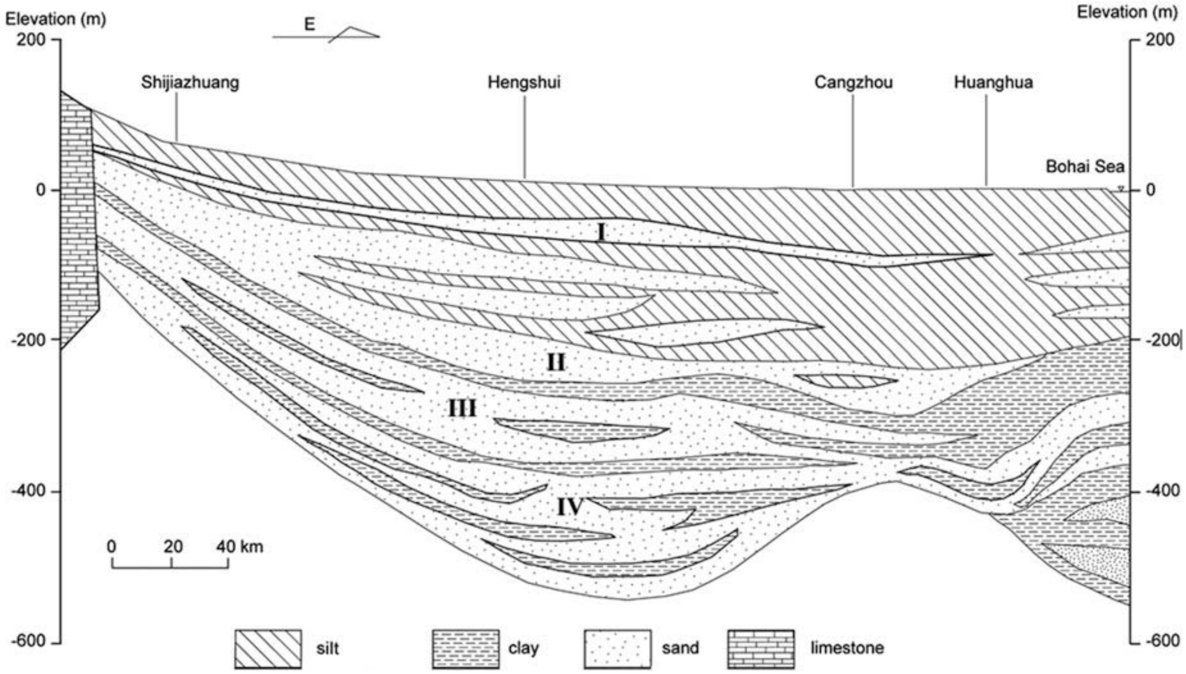

**Fig. 4** Cross section of the North China Plain in the west–east direction showing the general hydrogeological settings (modified from Chen et al., 2005)

**Table 1** Water resource statistics (in the year of 2006) for the Hai River Basin that includes the North Chain Plain (unit: $10^9$ $m^3$)

| Region | | Beijing | Tianjin | Hebei[a] | Henan | Shandong | Total |
|---|---|---|---|---|---|---|---|
| Total area ($km^2$) | | 16,800 | 119,20 | 171,624 | 15,336 | 30,942 | 246,622 |
| Precipitation | | 7.527 | 5.580 | 74.326 | 8.033 | 14.454 | 109.92 |
| Total available water resources | Surface water | 0.667 | 0.662 | 4.044 | 1.109 | 0.552 | 7.034 |
| | Groundwater | 1.816 | 0.443 | 9.067 | 1.985 | 2.37 | 15.68 |
| | Total | 2.483 | 1.105 | 13.11 | 3.094 | 2.922 | 22.71 |
| Water supply | Surface Water | 0.636 | 1.610 | 3.845 | 1.532 | 4.846 | 12.469 |
| | Groundwater | 2.434 | 0.676 | 16.230 | 2.666 | 1.832 | 23.838 |
| | Other | 0.36 | 0.010 | 0.066 | 0.002 | 0.083 | 0.521 |
| | Total | 3.43 | 2.296 | 20.142 | 4.200 | 6.761 | 36.829 |
| Water use | Agricultural | 1.205 | 1.343 | 15.036 | 2.851 | 5.781 | 26.216 |
| | Industrial | 0.620 | 0.443 | 2.609 | 0.819 | 0.363 | 4.854 |
| | Municipal | 1.443 | 0.461 | 2.379 | 0.453 | 0.577 | 5.313 |
| | Ecological | 0.162 | 0.049 | 0.117 | 0.077 | 0.039 | 0.444 |
| | Total | 3.430 | 2.296 | 20.142 | 4.200 | 6.760 | 36.828 |
| Water consumption | | | | | | | 27.052 |

[a] Hebei Province listed above includes not only the plain areas but also the mountain terrains. Data source: Water Resources Bulletin of 2006 for the Hai River Basin that includes the NCP.

resources amount, water supply, water use, and water consumption can be summarized in Table 1.

The statistical data in Table 1 are for the entire Hai River Basin, which as mentioned above, includes the NCP as defined in this study (136,000 $km^2$) plus mountain terrains to the west of the NCP (approximately 110,000 $km^2$). Therefore, the total available water resource of about 22 billion $m^3$ is actually overestimated for the NCP as defined in this study. The water uses, including agricultural, industrial, municipal, and ecological, however, are mainly concentrated on the plain area. Therefore, the total water uses (over 36 billion $m^3$) reasonably reflect the actual situation in the NCP. Even if water consumption is considered, that is, water uses minus the return flows to the hydrologic system, the net value of 27 billion $m^3$ is still greater than the total available water resources. From Table 1 it can be seen that the water uses are nearly equal to the water supply, because the "supply-decided" water use model has been adopted in China to coordinate the relationship between water resources and social/economic development. However, actual consumptive water uses are more than the total available water resources (by approximately 5 billion $m^3$ or nearly 22% of total available water resources). This indicates that the NCP is using water resources either from the groundwater storage or from outside sources. The numbers in Table 1 show that groundwater accounts for approximately 62% of the total water supply.

## Projected Water Demands, Water Supply, and Deficit

Future water demands have been projected based on the increasing rate of population, economic development, and ecological water requirements. The water demands in three major categories (municipal, rural, and ecological water demands) were projected for the years of 2010 and 2030 (Table 2). Compared with the situation in 1998, municipal water demand will be doubled by 2030, and ecological water demands will also have an obvious increase, while rural water demands will decrease slightly (Fig. 5).

By recycling wasted water, implementing new water supply projects, and utilizing sea water (shown as "others" in Table 3 and Fig. 6), the total surface water

**Table 2** Projected water demands for 2010 and 2030 compared with the 1998 data (unit: $10^9$ $m^3$)

| Regions | Municipal | | | Rural | | | Ecological | | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1998 | 2010 | 2030 | 1998 | 2010 | 2030 | 2010 | 2030 | 1998 | 2010 | 2030 |
| Beijing | 1.99 | 2.60 | 3.27 | 1.89 | 1.79 | 1.59 | | | 3.88 | 4.39 | 4.86 |
| Tianjin | 1.24 | 2.16 | 2.72 | 2.29 | 2.22 | 2.13 | | | 3.53 | 4.38 | 4.85 |
| Hebei | 2.73 | 4.71 | 6.84 | 13.79 | 12.73 | 12.49 | | | 16.52 | 17.43 | 19.32 |
| Henan | 0.69 | 1.02 | 1.44 | 1.99 | 1.89 | 1.76 | | | 2.68 | 2.91 | 3.20 |
| Shandong | 0.71 | 1.14 | 1.60 | 7.22 | 6.94 | 6.90 | | | 7.93 | 8.08 | 8.51 |
| NCP | 7.36 | 11.63 | 15.87 | 27.18 | 25.57 | 24.87 | 6.58 | 10.01 | 34.54 | 43.78 | 50.75 |

*Note*: The data are from the report of the Ministry of Water Resources (1998).

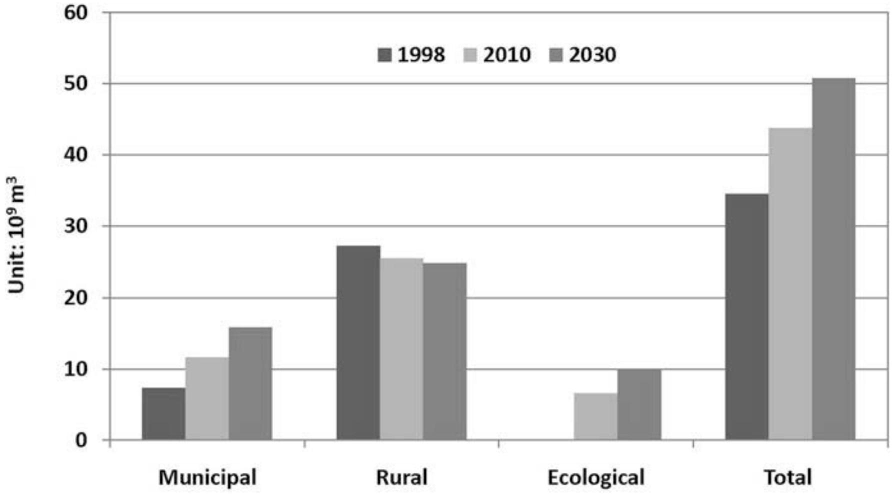

**Fig. 5** Projected water demands for three main water sectors in 2010 and 2030

**Table 3** Projected annual water supply in 2010 and 2030 (unit: $10^9$ $m^3$)

| Region | Surface water | | | Groundwater | | | Others[a] | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1998 | 2010 | 2030 | 1998 | 2010 | 2030 | 1998 | 2010 | 2030 | 1998 | 2010 | 2030 |
| Beijing | 1.44 | 1.51 | 1.46 | 2.20 | 2.37 | 2.15 | 0.21 | 0.45 | 0.62 | 3.84 | 4.33 | 4.23 |
| Tianjin | 1.67 | 1.78 | 1.79 | 0.65 | 0.60 | 0.56 | 0.63 | 0.51 | 0.54 | 2.95 | 2.89 | 2.89 |
| Hebei | 5.53 | 5.38 | 5.53 | 10.76 | 10.35 | 10.20 | 1.88 | 2.63 | 3.08 | 18.17 | 18.37 | 18.81 |
| Henan | 1.18 | 1.28 | 1.18 | 1.62 | 1.60 | 1.54 | 0.6 | 0.62 | 0.68 | 3.40 | 3.50 | 3.40 |
| Shandong | 0.64 | 0.58 | 0.58 | 2.40 | 2.50 | 2.50 | 3.66 | 3.70 | 3.82 | 6.70 | 6.78 | 6.90 |
| NCP | 10.46 | 10.53 | 10.54 | 17.63 | 17.42 | 16.95 | 6.98 | 7.91 | 8.74 | 35.06 | 35.87 | 36.23 |

*Note*: The data are from the report of the Ministry of Water Resources (1998).

[a] Others represent the water supply diverted from the Yellow River, recycled wasted water, and sea water.

supply will have slightly increased by the year of 2010 and 2030. But compared with the increasing trend of the total water demands, total water supply is not projected to increase significantly. Moreover, groundwater supply may decrease slightly. The projected annual water supply of the five provinces and municipalities in 2010 and 2030 is summarized in Table 3 (Ministry of Water Resources of PRC, 1998). Overall, the municipal water demands are projected to be more than doubled while the rural water demands would be

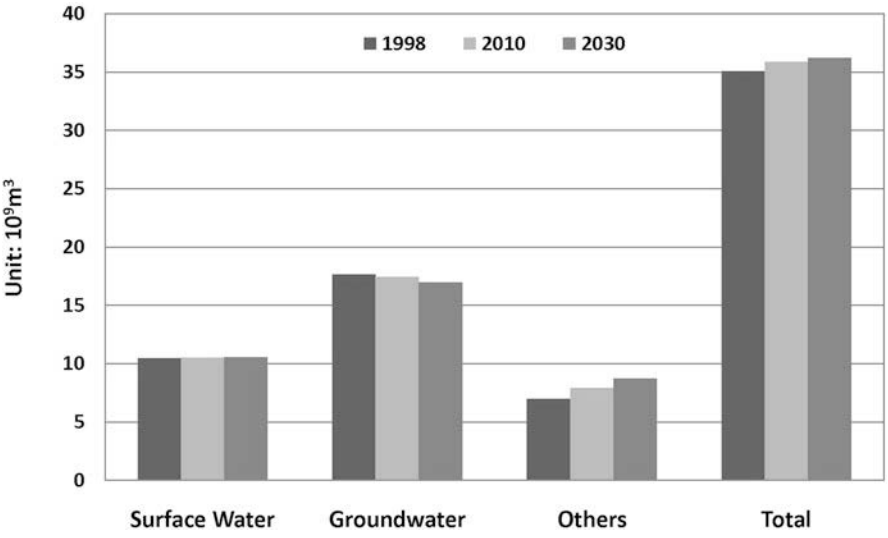

**Fig. 6** Projected water supply from various sources in 2010 and 2030

either steady or slightly decrease. The ecological water demands would have a significant increase, reflecting a new awareness on environmental protection.

Based on Tables 2 and 3, it can be seen that the deficit between water demands and water supply is around 7.9 billion m$^3$ by 2010 and will grow to 14.5 billion m$^3$ by 2030. Even though the middle route of the South-to-North Water Transfer (SNWT) project, a plan to divert water from the upper, middle, and lower reaches of the Yangtze River to the northern and northwestern parts of China, is planned to divert 13 billion m$^3$ water to the NCP by the year 2050 and play a positive role in alleviating the water shortage there in the long run, the transferred water will only target limited areas and mainly for municipal and industrial water uses (Ruan et al., 2004). Therefore, the deficit between the growing water demands and the finite water supply will become more and more acute.

## Key Issues in Water Resources Development and Management

It is an undisputed fact that the NCP is facing serious water shortage. Most rivers have been drying up or been changed to seasonal rivers. The groundwater table declines continuously and brings a series of adverse consequences – land subsidence, seawater intrusion, wetland loss, and pumping cost increase. Competition for water resources among different water use sectors becomes more and more intense. Besides the challenges in finite water quantity, water quality degradation is another important issue. According to the "*Water Resources Bulletin*" of the Hai River Basin in 2006, the discharged wastewater amount had been doubled from 1980 to 2000. The surface water quality shows an obvious trend of deterioration, and the pollutants gradually enter groundwater, with an obvious increase of some important water quality indexes like $NH_4$-N, $NO_3$-N, and $Cl^-$. How to sustainably utilize and manage the finite water resources to meet various demands as well as maintain an acceptable water quality and eco-environment is a huge challenge. In addition, the middle route of the SNWT project is planned to divert 13 billion cubic meters water to the NCP region by 2050. To what degree will it alleviate the water shortage in the NCP and how will it impact the eco-environment of this area will be an important issue as well.

## Methodologies and Tools to Address Sustainability

### General Definition of Groundwater Sustainability

Sustainability is a complex subject which integrates the considerations from social, economic, and environmental aspects. In a broader sense, sustainable development includes conservation of the environment, economic efficiency, and social equity. The best-known definition of sustainability or sustainable development is by the World Commission on Environment and Development in 1987, which defines sustainability as "forms of progress that meet the needs of the present without compromising the ability of future generations to meet their needs." This definition sets an ideal premise and a general concept but is not specific enough for real application.

Kinzelbach et al. (2003) brought forward the definition of sustainable water management, which is a management practice that generally avoids irreversible and quasi-irreversible damage to the water resource and the natural resources linked to it and conserves in the long term the ability of the resource to extend its services. They stated that usually it is easier to define what is unsustainable than what is, and non-sustainable is a practice which is hard to change but cannot go on indefinitely without running into a crisis. Non-sustainability shows in (1) depletion of a finite resource, which cannot be substituted; (2) accumulation of substances to harmful levels; (3) unfair allocation of a resource leading to conflict; and (4) runaway costs. The specific definition of groundwater sustainability can be specified as (1) abstraction rate less than natural replenished rate; (2) limitation of drawdowns; (3) guarantee of minimum downstream flow; and (4) prevention of groundwater pollution (Kinzelbach et al., 2003).

In this study the authors mainly explore the sustainability of groundwater resources in the NCP from the consideration of natural science. Interdisciplinary study to explore sustainability comprehensively is indispensible, but a clear understanding of the natural groundwater resources underlying physical flow systems is a prerequisite for comprehensive sustainability analysis.

### Methodologies and Scientific Tools for Sustainability Studies

Since sustainability is a complex, multi-faceted concept, which may be defined anew for specific circumstances, the methodologies for sustainability studies may also depend on each specific case. However, some methodologies have been commonly used and serve as the basis for sustainable groundwater management. Those include (1) using models (flow and/or transport) and experimental methods to describe the physical system; (2) integrating with surface and soil water to explore the entire hydrologic system; (3) optimization and prediction; (4) possibly coupling with economic and societal preferences; and (5) coping with uncertainty (Kinzelbach et al., 2003). Groundwater modeling is considered an essential tool of water resources studies. Groundwater models can reproduce the historical hydrodynamics, predict the future variations, optimize the water resources development, and test different water resources management scenarios in a convenient and economical way. Yet the current methods of analysis and complexity of the systems often cause uncertainty that casts doubts on the credibility of modeling. Thus independent data sources for model calibration and verification are indispensible. Experimental methods and remote sensing techniques are essential supplementary means to modeling.

### Socio-economic Considerations

It is recognized that sustainable development includes three "pillars" – environmental, economic, and social. The scope of social and economic considerations within sustainable development concept is obviously very wide; however, it is becoming increasingly clear that there is a need for more integration and balance among the pillars of sustainable development. As Kinzelbach et al. (2003) mentioned, "Natural science has to interface to economics and implementation in order to be really useful." The sustainable development concept is not a simple project of the natural sciences, instead it needs broad and cross-disciplinary analysis. The most important part of sustainable development is how to practically put sustainability principles into actions in the real world.

## Regional Groundwater Flow Modeling

In this section, we describe the development of a regional groundwater flow model for the NCP. Such a model is essential for understanding the groundwater flow system in the NCP and for evaluating the various options for sustainable management of groundwater resources in the NCP. The focus of this section is to present the results of model construction and calibration. An overall flow budget for the NCP will be quantified and discussed. However, a more comprehensive analysis of various management options for NCP groundwater resources will be presented elsewhere in the future.

## Conceptual Model

The NCP groundwater system can be described as three-dimensional, heterogonous, anisotropic, and transient flow system. As described in section "Surface Water and Aquifer System", the Quaternary

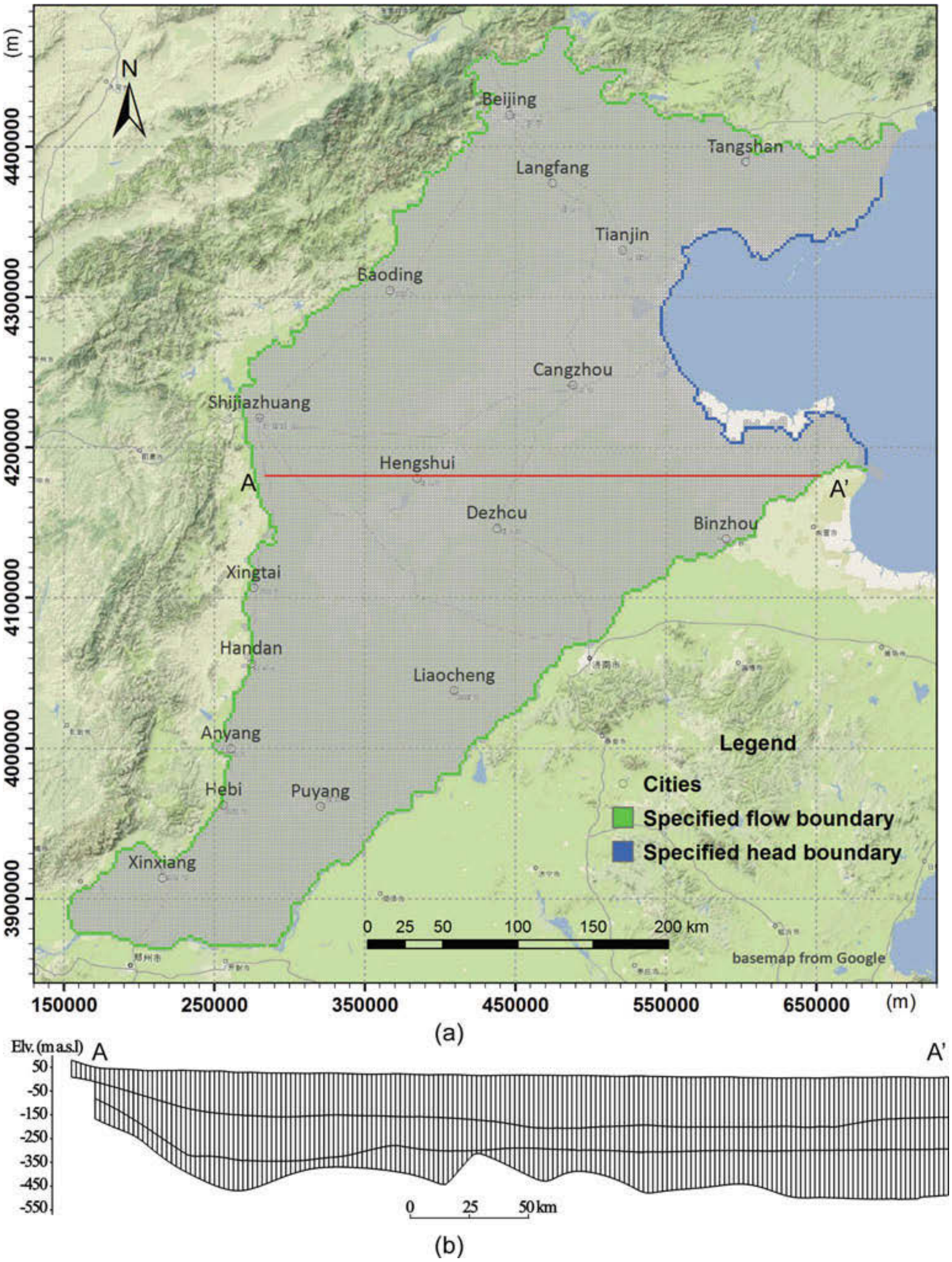

**Fig. 7** (**a**) Horizontal discretization of the model domain and boundary conditions and (**b**) vertical discretization

formations in the NCP can be divided into four major aquifer units. The first and second units are referred to as the "shallow aquifer" and the third and fourth units as the "deep aquifer." The horizontal groundwater flow is dominant in the NCP because of the wide horizontal distribution and large thickness of the aquifer layers, whereas the vertical flow is only significant in areas with large pumping. During the simulation period (2000–2008) the aquifer system of NCP is not at equilibrium and the source/sink terms of the model fluctuate seasonally. Spatially, the hydraulic properties of the aquifer are highly heterogeneous.

## Numerical Model Construction

### Spatial and Temporal Discretization

The entire model domain is discretized into 320 rows and 323 columns, and the grid cells are uniformly spaced (Fig. 7) with a size of 2×2 km. Vertically the

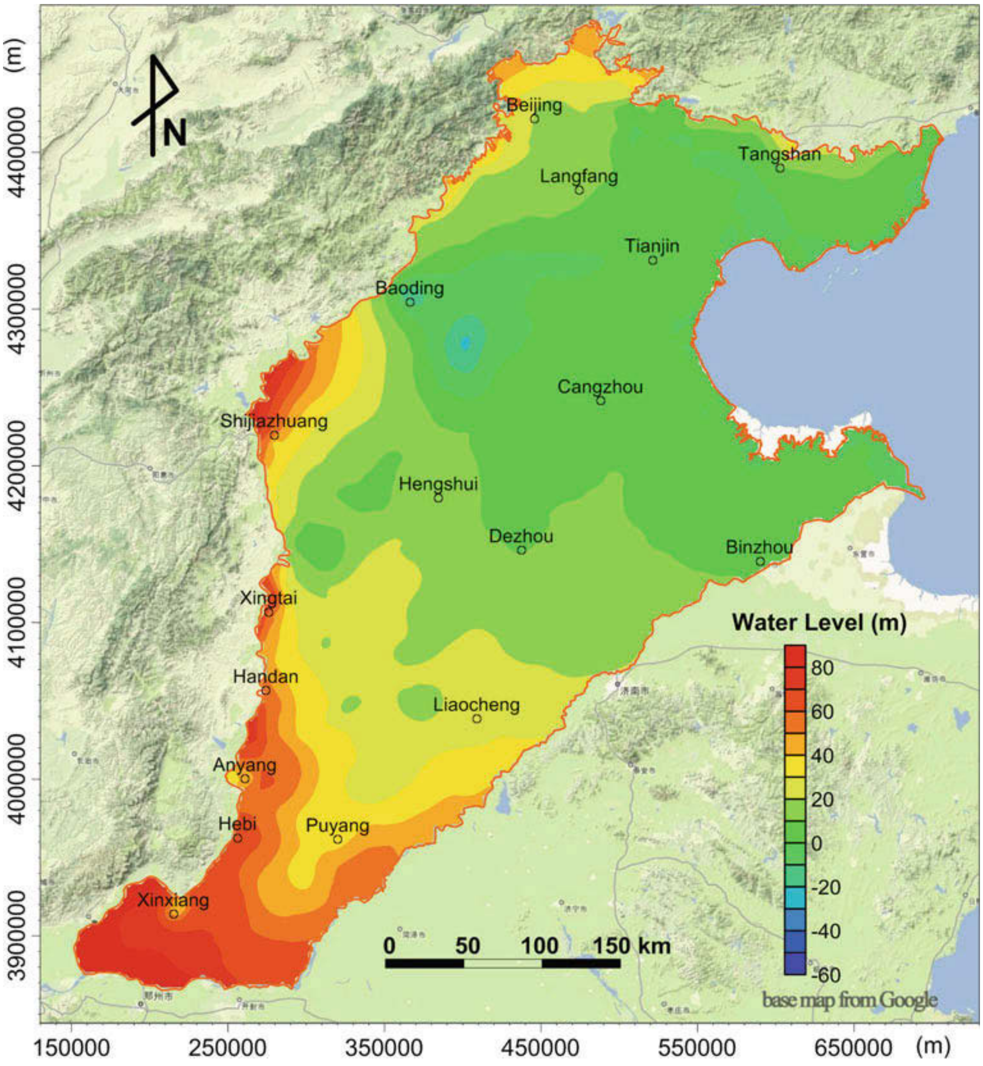

**Fig. 8** Model-calculated head distributions for the shallow aquifer in 2000

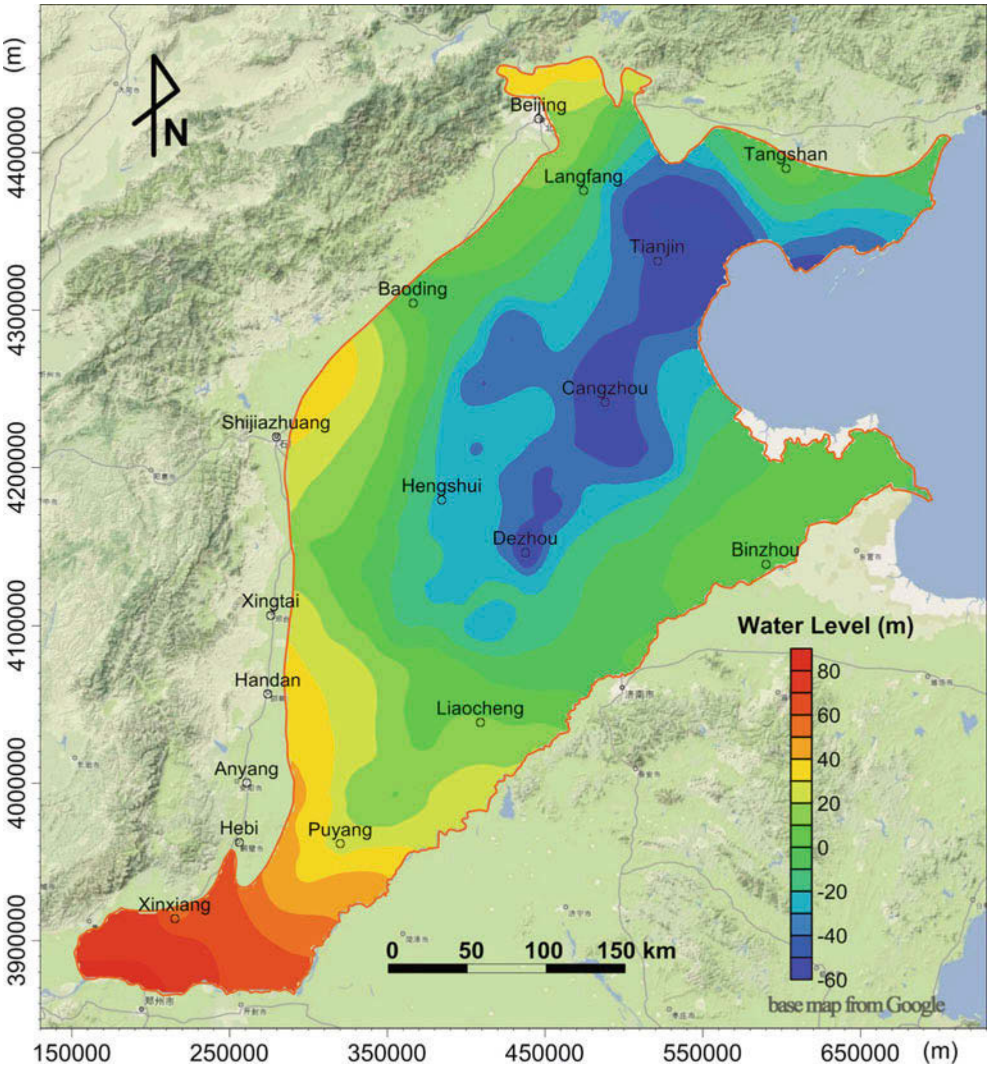

**Fig. 9** Model-calculated head distributions for the deep aquifer in 2000

model is discretized into 3 layers (Fig. 7), resulting in a total of 292,500 grid cells. Layer 1, containing the first and second physical aquifer units, represents the shallow aquifer; layer 2 represents the third aquifer unit; and layer 3 represents the fourth one.

Simulations are carried out under transient conditions for 108 stress periods that began on January 1, 2000, and ended on December 31, 2008. The length of each stress period is 1 month.

## Boundary Conditions

The boundary conditions determine the location and quantity of flow coming into or out of the model domain; therefore, the selection of the appropriate boundary type is a major concern in model construction. The northern and western lateral boundaries of the shallow aquifer accept flow from the Yan Mountains and the Taihang Mountains. These boundaries thus are defined as specified flow boundaries. The southern and southwestern lateral boundaries receive leakage from the Yellow River and are also defined as specified flow boundaries. The specified head condition is used to represent the eastern lateral boundary bordering the Bohai Gulf. The lateral boundaries of the deep aquifer and the base of the fourth aquifer are simulated as no-flow boundaries.

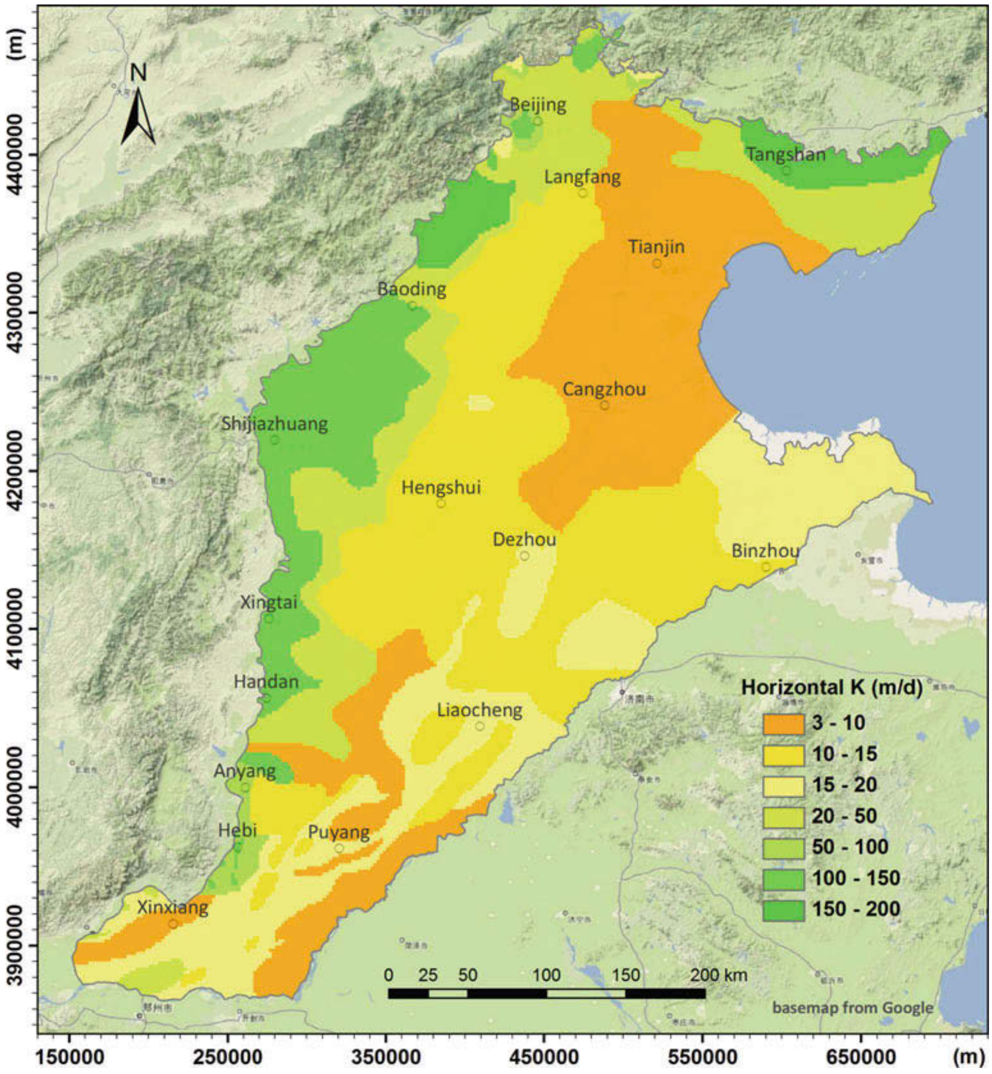

**Fig. 10** Model-calibrated horizontal hydraulic conductivity for the shallow aquifer

## Recharge and Discharge

The primary recharge to the shallow aquifer is the infiltration of precipitation. Other recharge items of this region include returning flow from irrigation, leakage of surface water, and lateral recharge from the mountainous terrains. Groundwater pumping is the primary discharge from the aquifer system. Evapotranspiration and lateral discharge to the Bohai Gulf are two other types of discharge in the shallow aquifer.

## Initial Condition

The initial condition represents the head distribution at the beginning of the transient simulation. The initial condition for the transient model is developed in this study through a quasi-steady-state model that reflects the head field immediately prior to the start of the transient model. The results of the calibrated quasi-steady-state model as shown in Figs. 8 and 9 are used as the initial condition for the transient simulation.

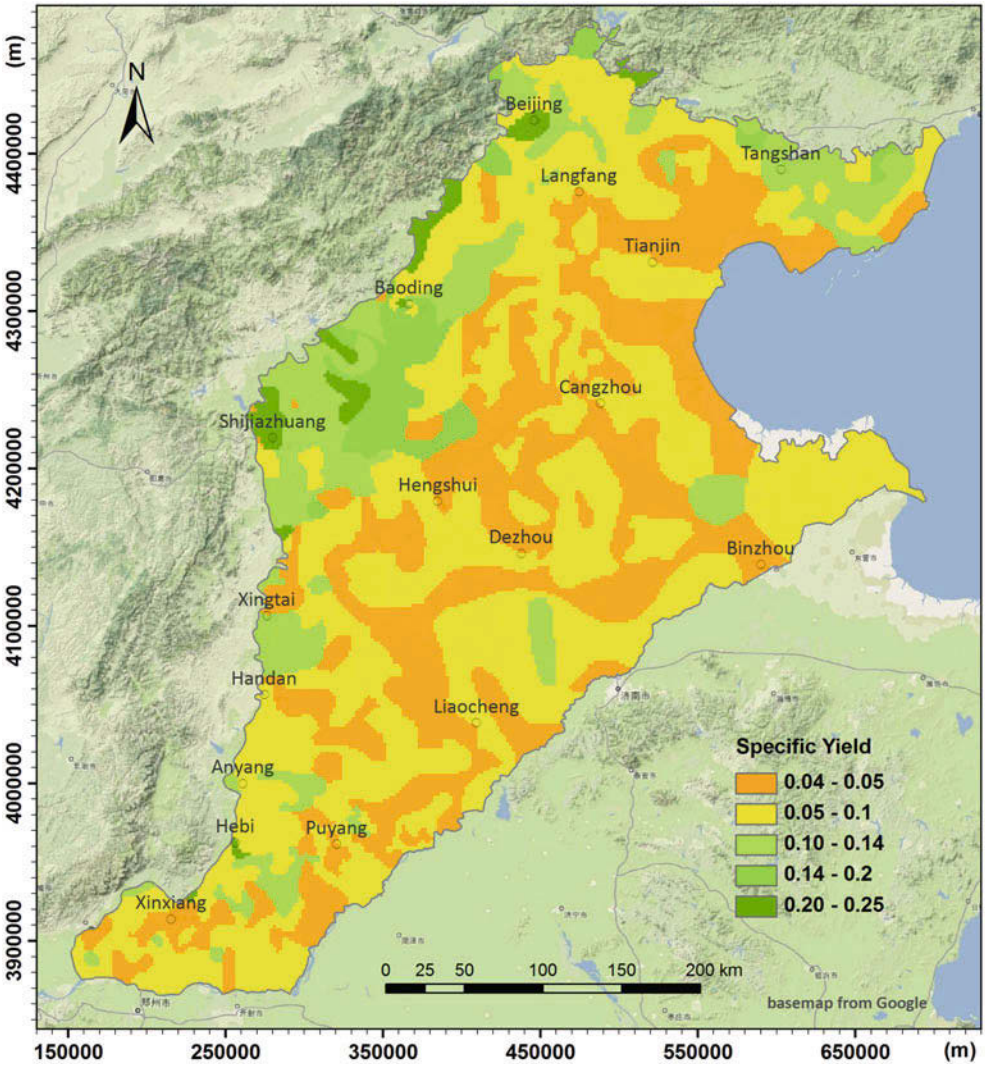

**Fig. 11** Model-calibrated specific yield for the shallow aquifer

## Model Calibration

Because of the large scale (136,000 km$^2$) of the NCP, the available data set does not justify a detailed model calibration. In this study the primary objective of the model calibration is to adjust the hydraulic conductivities and specific yields to achieve an overall agreement between the simulated and measured heads. The computed water budget from the flow model is also used as an important consideration in judging the quality of the overall model calibration.

Figures 10 and 11 show the final calibrated hydraulic parameters. Distribution and values of these parameters are supported by relevant literatures and previous studies (e.g., Dong, 2006; Kendy et al., 2003; Shimada et al., 2006; Wang, 2006; Zhang et al., 2006). Calculated groundwater levels are compared with the observed values at available observation locations as shown in Fig. 12.

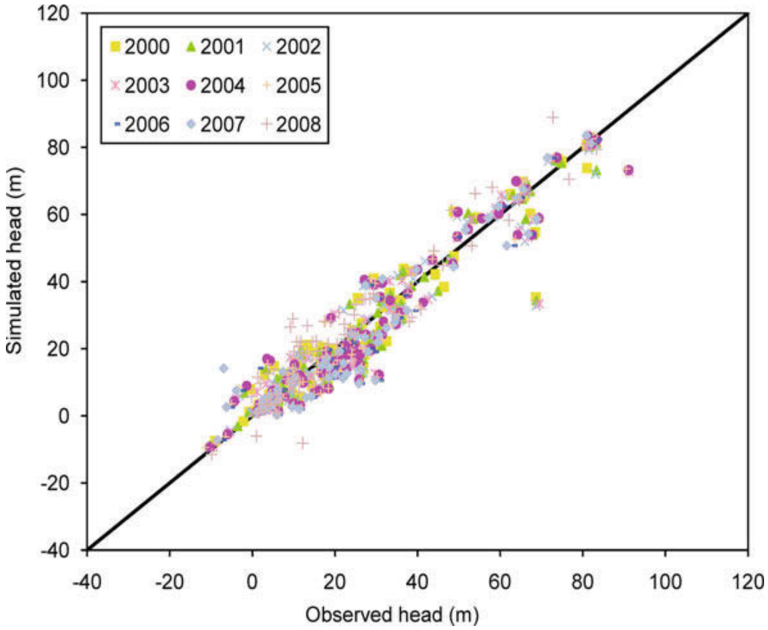

**Fig. 12** Comparison of the model-calculated heads with the observed heads for all observation locations from 2000 to 2008

## Model Results

The NCP groundwater flow model successfully simulates the groundwater flow pattern and the calculated water budget compares favorably with independent estimates from other sources. Figures 13 and 14 show the groundwater levels in the shallow aquifer and the deep aquifer, respectively. The contour maps of calculated heads in the unconfined aquifer show that groundwater flows from the mountain front along the north and west boundaries of the plain toward the central part of the plain and Bohai Gulf. In several large metropolitan areas near the western mountain front, such as Beijing, Baoding, and Xingtai, over-exploitation has led to extensive groundwater depression cones (Fig. 13). In the central part of the NCP, groundwater is mainly exploited from the deep aquifer, which has resulted in several large groundwater depression cones around Dezhou, Cangzhou, and Tianjin (Fig. 14).

The water balance during the simulation period is analyzed and presented in Table 4 and Fig. 15. The various inflow and outflow items are generally consistent with those from previous studies (e.g., Dong, 2006; Wang, 2006). The average annual groundwater recharge is around 18 billion m$^3$, while the average annual groundwater pumping is about 22 billion m$^3$. The discrepancy of approximately 4 billion m$^3$ is compensated from the groundwater storage. This indicates unsustainable groundwater development in the NCP, which causes continuous groundwater level decline and subsequent negative environmental consequences. The basin-scale groundwater flow model constructed in this study will provide a useful tool for regional groundwater resource evaluation and sustainable groundwater management. Various scenarios related to climatic changes and human activities will be evaluated and presented elsewhere in a future publication.

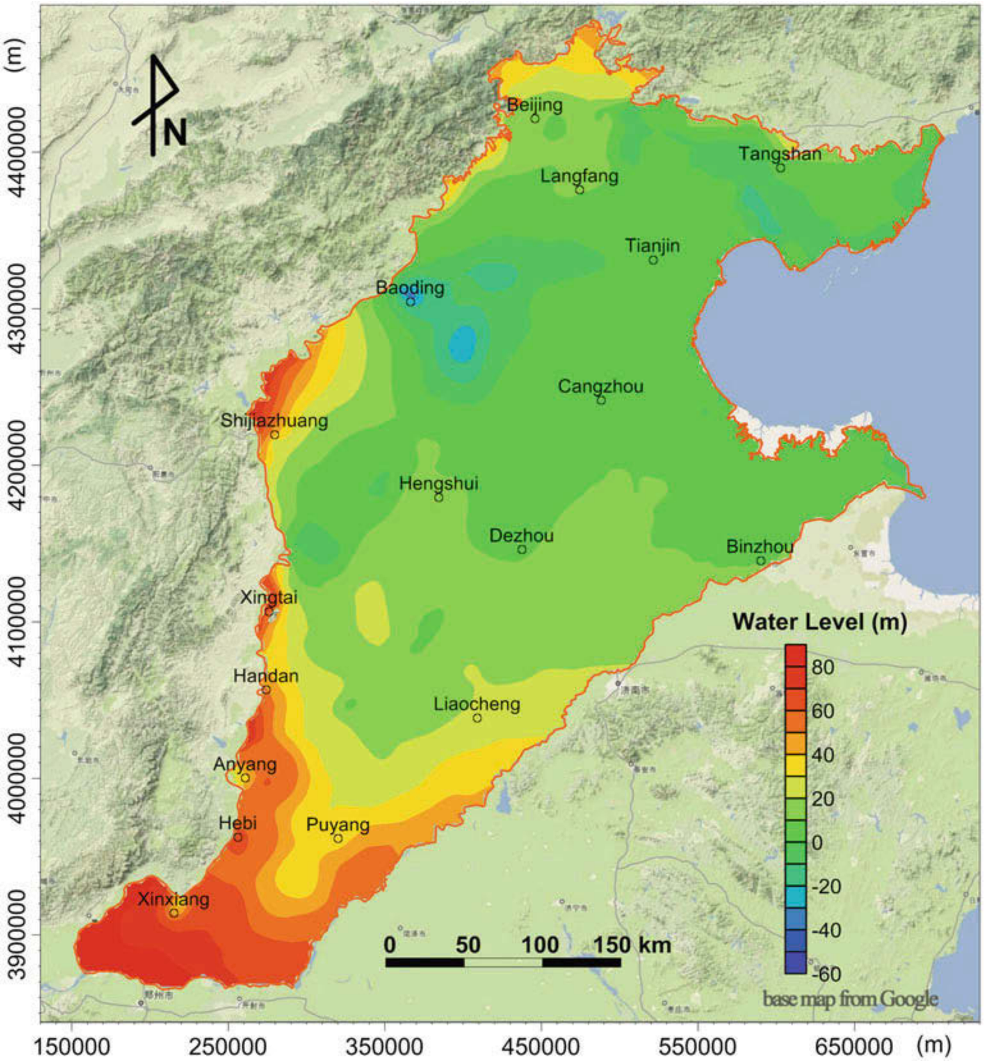

**Fig. 13** Model-calculated head distributions for the shallow aquifer in 2008

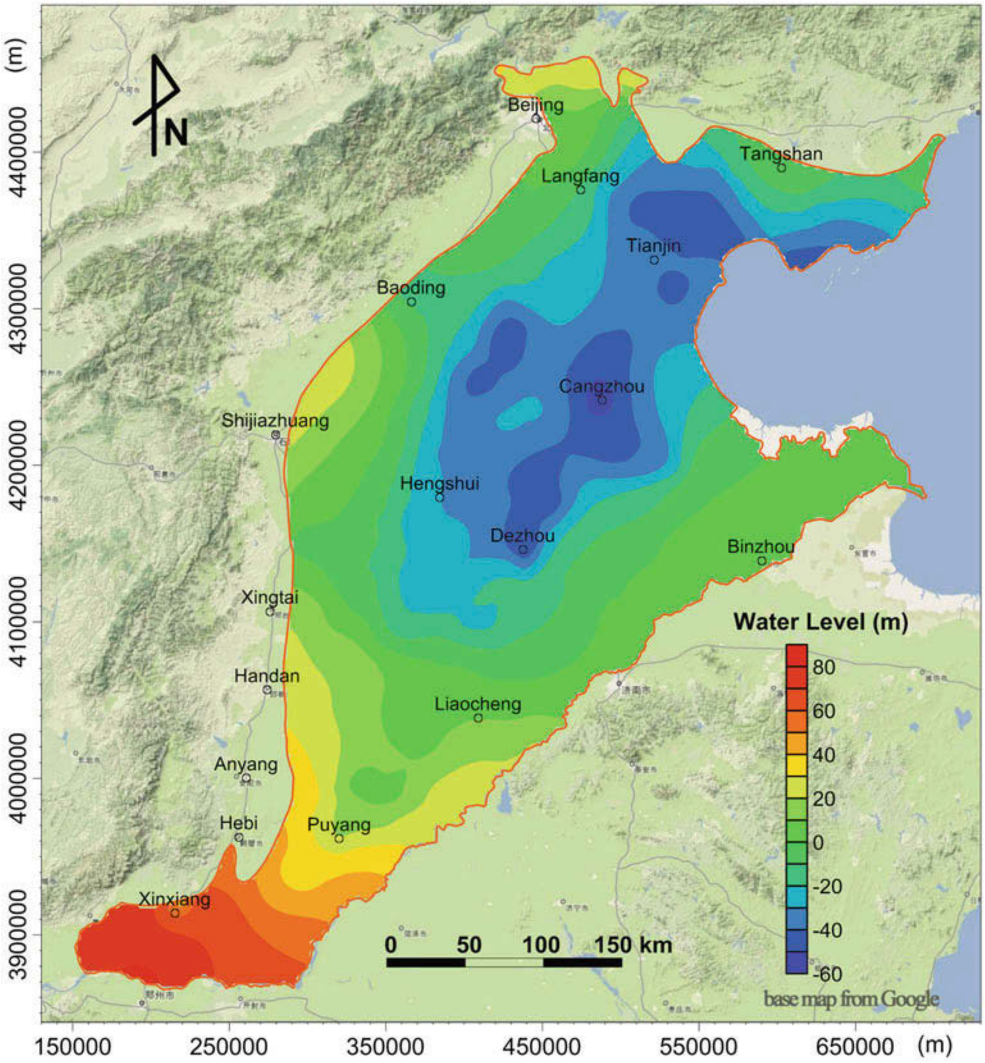

**Fig. 14** Model-calculated head distributions for the deep aquifer in 2008

**Fig. 15** Calculated annually averaged groundwater budgets between 2000 and 2008

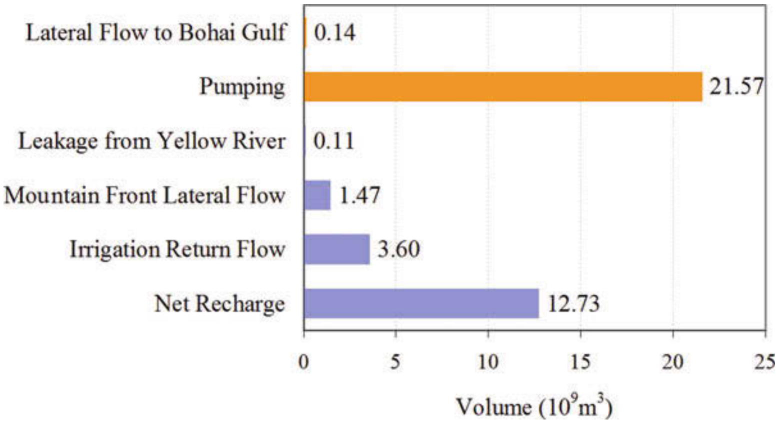

**Table 4** Calculated annual water budget from the NCP groundwater flow model between 2000 and 2008

| Budget items | Volume ($10^9$ $m^3$) | Percentage (%) |
|---|---|---|
| *Inflow* | | |
| Groundwater recharge | 12.73 | 71.08 |
| Irrigation return flow | 3.60 | 20.10 |
| Mountain front lateral flow | 1.47 | 8.21 |
| Leakage from Yellow River | 0.11 | 0.61 |
| Total | 17.91 | 100.00 |
| *Outflow* | | |
| Pumping | 21.57 | 99.37 |
| Lateral flow to Bohai Gulf | 0.14 | 0.63 |
| Total | 21.71 | 100.00 |
| *Storage depletion* | 3.52 | |

## Summary and Conclusions

The urgency and the significance of studying NCP water problems are obvious. The assessment of sustainability of groundwater resources in the NCP is not only needed for mitigating the conflicts between limited water resources and the increasing water demands from various sectors, but is also instructive for many similar places looking for means of sustainable groundwater development and management.

In this case study, a finite difference numerical model has been developed for the NCP based on the MODFLOW (Harbaugh et al., 2000) groundwater modeling system. The model was calibrated against groundwater levels in the shallow and deep aquifers and by comparing with flow budgets observed or inferred in previous studies. The simulated groundwater levels in the aquifer system show an overall agreement with the historical records. The total water budgets indicate that there is more outflow than inflow, causing the aquifer storage to be depleted continuously and suggesting unsustainable groundwater resource development.

The regional groundwater flow model provides a useful tool for analyzing various groundwater development and management scenarios. However, there is no scenario alone that can solve the groundwater depletion problem in the NCP (Liu et al., 2008). The sustainable development of groundwater resources in the NCP requires an integrated planning that considers water resources, land use, and climate change as well as the social and economic factors (Kendy et al., 2007). This study is only the first step toward a comprehensive effort to develop effective management strategies that ensure long-term, stable, and flexible water supplies to meet growing municipal, agricultural, and industrial water demands in the NCP while simultaneously mitigating negative environmental consequences. In the future, interdisciplinary studies to integrate natural science, economic, and social considerations should be pursued.

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# Groundwater Management in a Land Subsidence Area

Kazuki Mori

**Abstract**

In a stressed hydrological environment, the practice of groundwater management is important for sustainable water use. Land subsidence in the Nobi Plain in the central part of Japan has produced the largest sea-level zone in Japan. A good correlation is found between volume of land subsidence and groundwater withdrawal, and the regression line indicates the value of the optimum amount of groundwater withdrawal at which the volume of land subsidence becomes zero. The artesian head of confined groundwater in Japan began to increase over the first half of the 1980s as a consequence of both the regulation of groundwater withdrawal and water economisation. The unexpected rise in groundwater level has resulted in a buoyancy of underground structures. In contrast to the past state of affairs, lowering the groundwater level as economically as possible is now a pressing matter in the greater metropolitan area. As a result of groundwater conveyance into polluted surface waters since the latter half of the 1990s, the effect of an improvement in water quality has become apparent. Comparison of the pre- and post-urbanisation state reveals a decrease in the rate of groundwater recharge owing to an enlargement of the impervious land area. It is worthy of special mention that coactions between local people, enterprises and administrative offices have fulfilled their function in terms of enhancing proper management and preserving a better environment for groundwater. An administrative body has also driven forward the actual enforcement of policy concerning the conservation of groundwater resources and the establishment of a symbiotic water environment.

**Keywords**

Groundwater management • Land subsidence • Sea-level zone • Optimal groundwater withdrawal • Water balance

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# Introduction

## Groundwater: No Alternative Water Resources

Groundwater has been increasing in importance as a usable resource to meet the rising demands imposed by human activity, as well as an indispensable water supply in emergency situations for example after a disastrous earthquake. Concurrently, the development of groundwater resources has sometimes been counterproductive with environmental damage due to improper utilisation. For instance, excessive withdrawal of groundwater for use in industry and eel-farming in the alluvial plain has caused irrecoverable environmental problems in which land subsidence and sea water intrusion are ubiquitously recognised in a littoral district (e.g. Mori, 1985). In regard to the annual change in groundwater level, a decline in the winter months is also remarkably realised as a result of concentrated withdrawal of groundwater for melting of snowfall on road surfaces. One can conclude from the regional characteristics affecting groundwater use as mentioned above that the groundwater balance under different spatial-temporal scales should be quantitatively clarified to provide information for the establishment of proper water use. That is why a full understanding of quantitative as well as qualitative properties of groundwater in relation to individual hydrogeological characteristics is significant for water sustainability.

In addition, groundwater is a fragile resource in relation to contamination as induced by domestic, agricultural and industrial activities. For sustainable utilisation of groundwater, protection of the vulnerable groundwater resource is a vital subject as restoration of polluted loads is extremely difficult on most occasions. In order to obviate groundwater resources against high risks of pollution, the groundwater recharge area must be recognised and kept under observation. Secondly, hazards for groundwater in the hydrogeological setting such as buried faults, where pollutants may spread into the confined aquifer system, should be identified.

## Necessity for Evaluating the Recharge Rate

Identification of unsustainable exploitation of fossil reserves could be deduced from the natural recharge rate of groundwater over a long time period such as geologic time, especially in the case of confined groundwater with a relatively long residence time. In the confined aquifer system, which is the most important form of water resource in the coastal areas in general, there have been few estimates made of recharge volume due to the limited practical methods to evaluate the arrival rate of percolated water to the aquifer. In the confined aquifer, where cation exchange is sometimes the dominant reaction, the natural recharge of groundwater was estimated on the basis of records of cation exchange reaction in argillaceous sediments since the last transgression (Yamanaka et al., 2005, 2007). In order to minimise resource depletion and associated disastrous human and ecological consequences, understanding of the recharge rate is indispensable.

In addition, the volume of groundwater resource in an aquifer system and its understanding are an important subject. A major issue for sustainable groundwater utilisation is, however, to grasp the natural recharge volume in the system, rather than the groundwater volume itself. This indicates that the time dimension should be taken into account for estimating the groundwater volume. On this point, a particular approach to groundwater management with special reference to the hydrological cycle has significant validity in clarifying the quantitative relationship between water on the Earth and human activity (Mori et al., 2003). In cases where the natural recharge volume of the groundwater is sufficiently large, the volume of the groundwater resource is not as important as the groundwater can be recharged within a short space of time. On the contrary, if the former is quite small, an irrecoverable problem would arise in terms of groundwater sustainability regardless of the groundwater volume. In this sense, what we have to understand for sustainable usage is the natural recharge rate of groundwater. Groundwater must be used with a consideration of this concept.

# Land Subsidence: Environmental Destruction Induced by Excessive Withdrawal of Groundwater

## Effect of Regulation of Groundwater Withdrawal

In Japan damages from floods and tidal waves are a rather frequent occurrence. Approximately 51% of the total population and 75% of the total property are concentrated in the alluvial plain, which takes up only 10% of the total area of the country. The Nobi Plain in the central part of Japan is a textbook-perfect region where both extensive utilisation and positive conservation of the groundwater resource have been practiced for years. The maximum depth of the Tertiary bedrock in the groundwater basin reaches up to 300 m. The comprehension of the hydrogeological and geochemical properties of the groundwater in the Nobi Plain has contributed to solutions for water resources management as well as the creation of a better environment.

The distribution of the total amount of land subsidence in the Nobi Plain for the years 1961–2008 is shown in Fig. 1. As seen in the figure, the total amount of subsidence in the Nobi Plain has attained approximately 1.6 m, and this produced the largest sea-level zone in Japan, with an area of 274 km$^2$. The concentration of chloride ions in confined groundwater in the plain is over 2,500 mg/L, and the area showing the highest concentration coincides with a zone of high intensity of withdrawal (Mori, 1987). It should be pointed out that the extrusion of fossil water from marine impermeable layers is a further source of higher concentrations of dissolved material in groundwater. Under such stressed environmental conditions, the practice of groundwater management in the study area is very important for sustainable water use and the rehabilitation of the environment (Mori, 1981).

Changes in groundwater level are significantly influenced by withdrawal, precipitation, irrigation water for paddy fields, improvement of river course and land use including surface covering. As shown in Fig. 2, secular changes in water table in the Nobi Plain show a tendency towards recovery in later years (Research Group for Land Subsidence in Tokai Three Prefectures, 2009). As is clearly inferred from Fig. 2, regulation of groundwater withdrawal was effective in improving land subsidence. Since the end of the 1970s, the total amount of land subsidence shows no marked increase, and the cumulative curve has remained at the same level. Secular changes in groundwater level and withdrawal in the Nobi Plain are also illustrated in Fig. 3. In addition to regulation of groundwater withdrawal, the development of alternative water resources including surface water to shift towards use of these alternative water resources as opposed to groundwater has produced a good result in terms of the upward tendency of groundwater level.

## Optimum Amount of Groundwater Withdrawal

In the 1970s, the recovery of groundwater level was the most important task in order to stop land subsidence exceeding 1.5 m in the littoral district. From

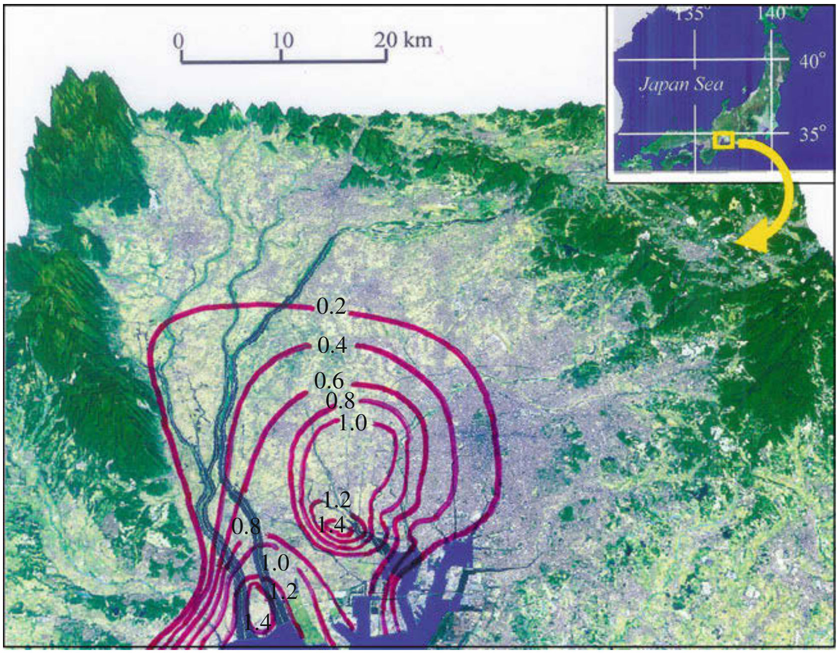
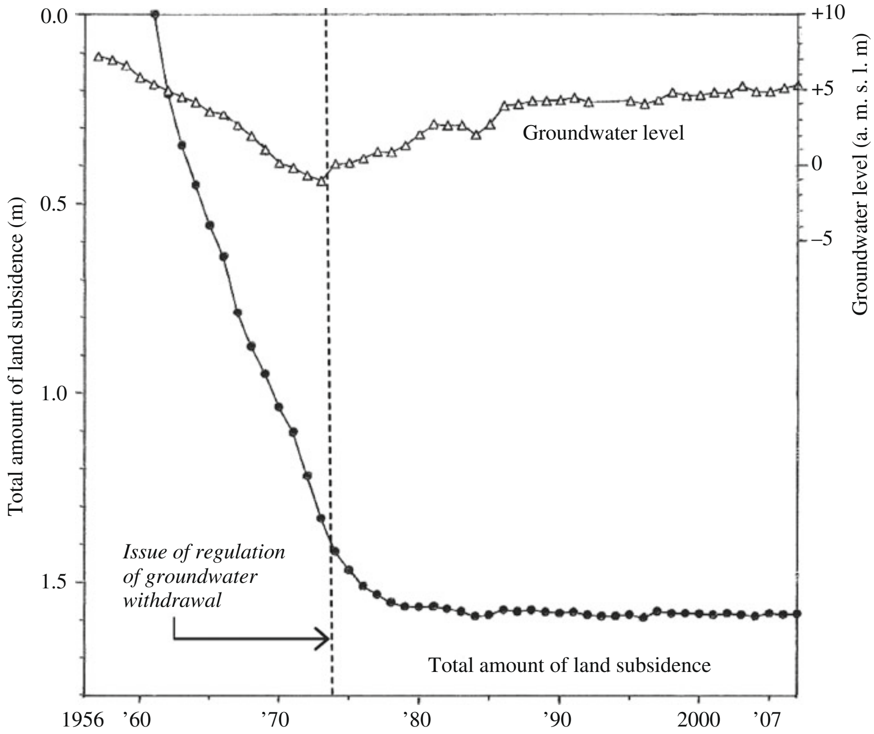


**Fig. 1** Distributions of the total amount of land subsidence in the Nobi Plain, central Japan, for the years 1961–2008 (unit in m)

**Fig. 2** Long-term changes in the total amount of land subsidence and groundwater level in the Nobi Plain (redrawn from Research Group for Land Subsidence in Tokai Three Prefectures 2009)



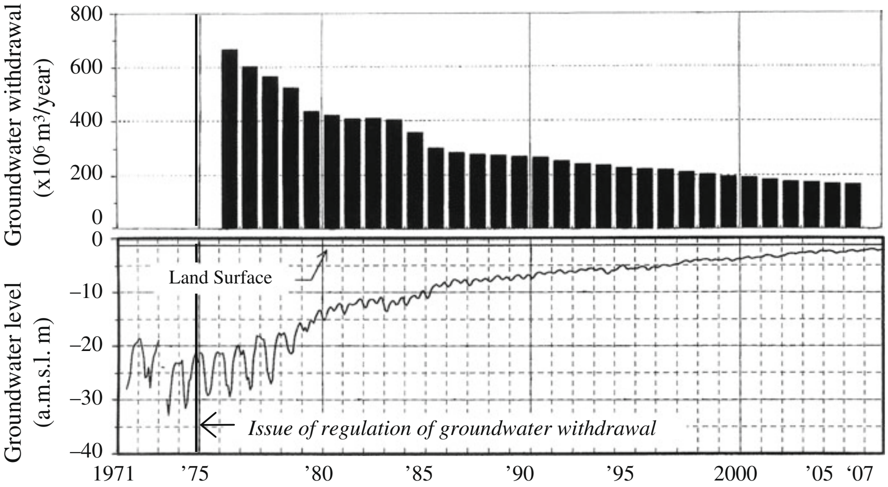


**Fig. 3** Secular changes in groundwater level and withdrawal in the Nobi Plain

this point of view, verifying the optimum amount of withdrawal and the efficient use of groundwater was vital for a land subsidence area. Data on the temporal change in annual volume of land subsidence and withdrawal amounts have been collected in the Nobi Plain since regulation of groundwater withdrawal began.

Figure 4 shows the relationship between annual volume of land subsidence and groundwater withdrawal in the Nobi Plain for each year after the regulation of groundwater withdrawal was introduced (modified from Iida et al., 1977). From this figure, a good correlation is found for both elements,

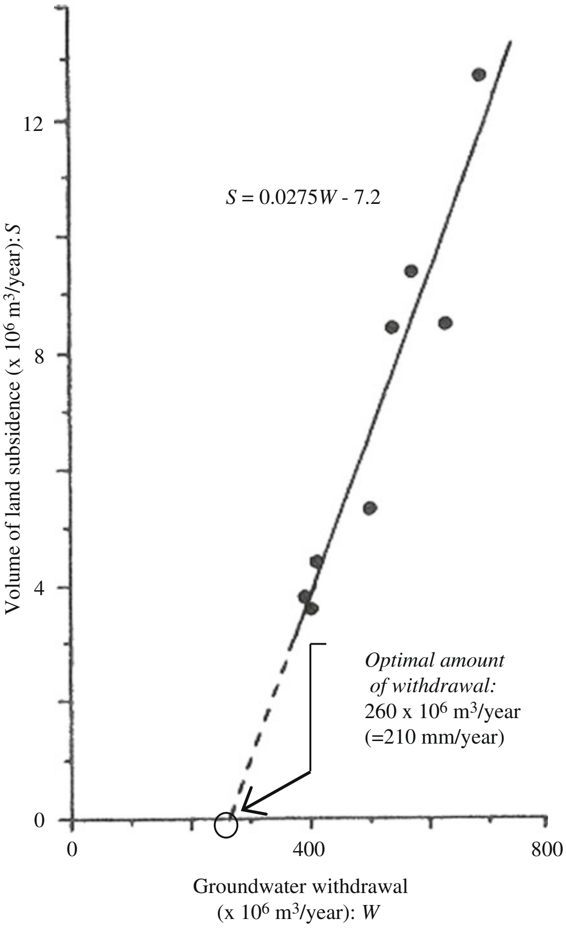


**Fig. 4** Relationship between volume of land subsidence (*S*) and groundwater withdrawal (*W*) in the Nobi Plain (modified from Iida et al., 1977)

and the regression line indicates the value of the optimum amount of withdrawal as 260 x $10^6$ $m^3$/year (=210 mm/year) at which the volume of land subsidence becomes zero.

## Recent Groundwater Issues in the Greater Metropolitan Area

The artesian head of confined groundwater in Japan, which had been dropping to meet the increasing demands for industrial water during the period of rapid economic growth from 1955–1975, has taken an upward turn since the first half of the 1980s as a consequence of both the regulation of groundwater withdrawal by local government and water economisation by enterprises. The unexpected rise in groundwater level has also resulted in buoyancy of underground structures. In contrast to the past state of affairs, lowering the groundwater level as economically as possible is now a pressing matter in the greater metropolitan area. In order to reduce sewerage expenditures for draining the pumped-up groundwater, the promotion of effective utilisation of the groundwater resource became an important problem.

On the other hand, there is still no visible prospect of a resolution of the problem of lake eutrophication in densely populated urban areas, originating from the relatively longer residence time of the water and the increase in pollutant load. Consequently, how to purify the highly contaminated shallow lakes and small rivers in large cities is a task that remains to be solved. As a result of groundwater conveyance into polluted surface water since the latter half of the 1990s, an improvement in the water quality has become apparent. This fact should enable us to kill two birds with one stone: purifying the contaminated surface water while at the same time reducing sewerage expenditures.

## Changes in Water Balance Attendant Upon Urbanisation

The hydrological cycle process has been transformed as a result of progressive urbanisation, and this type of transformation has a negative effect on society (Mori, 2004). From this point of view, it is considered that a better understanding of the quantification of the hydrological processes may form the basis for optimal and sustainable utilisation of water resources. The consequence of change in the water environment includes both qualitative and quantitative aspects (e.g. Hall, 1984). Since the qualitative changes in the water environment are closely linked to quantitative problems, both aspects should always be considered as related phenomena.

Figure 5 shows definite findings on the change in water balance in Nagoya City which has a population of 2.1 million (drawn from the data of Maeda, 1991). Changes in each component of groundwater balance in the study area were also investigated from natural and artificial aspects including leakage from water supply pipes. Numerical comparison of the pre- and post-urbanisation state reveals a decrease in the rates of groundwater recharge and evapotranspiration owing to the enlargement of the impervious area.

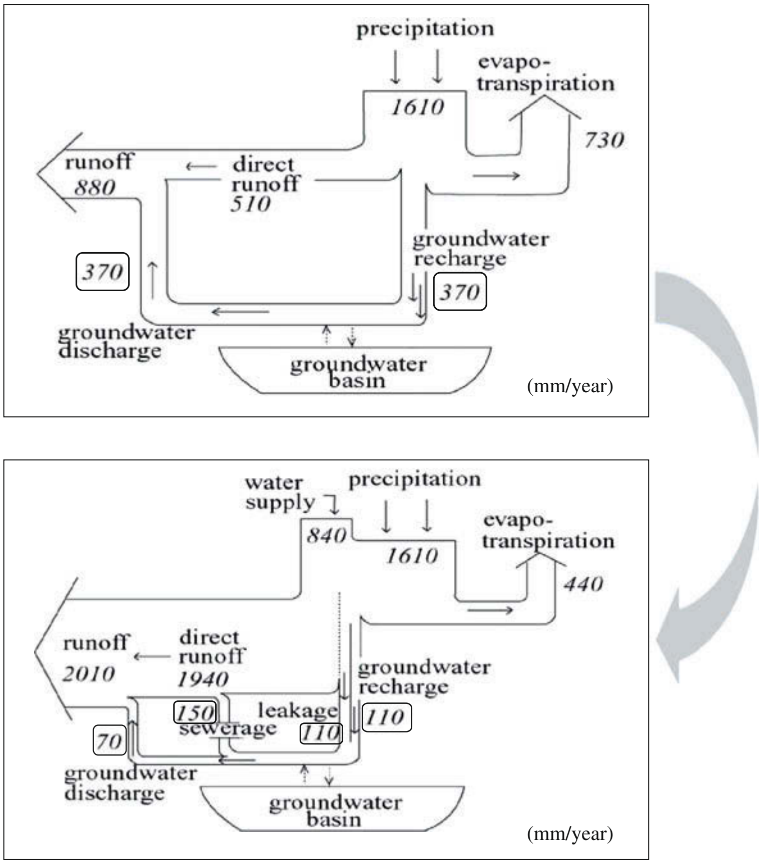


**Fig. 5** Changes in water balance between pre- and post- urbanisation in Nagoya City (drawn from the original data in Maeda, 1991)

The rate of annual evapotranspiration decreased to almost 60%, from 730 mm to 440 mm, due to the decrease in soil area, and groundwater recharge also decreased to approximately 30%, from 370 mm/year to 110 mm/year. From the above-mentioned facts, an artificial increase in the rate of groundwater recharge becomes an important problem in an urban area. The striking feature in the difference in water balance following the increase of population density is an input of water supply from outside of the catchment. It is also evident that the amount of direct runoff increases, whereas the base runoff reduces as compared with the rural landscape stage.

## Toward the Conservation and Sustainable Use of Groundwater

The management of water resources in urban areas so as to maintain a better condition is exceedingly important for proper regional development. From this point of view, a hydrological approach to conserve a better water environment is significant in clarifying the quantitative relationship between water on the earth and human activities. A particular approach to the conservation of the water environment, including the hydrological cycle, has significant validity in establishing a course of action for sustainability.

In order to pass such a favourable environment to the next generation, it is increasingly considered that the conservation of groundwater resources has substantial validity. In fact, comprehension of physical and chemical properties of groundwater in the Nobi Plain has contributed to the solution of the water resource management problem as well as the creation of a better environment. It should also be mentioned that groundwater resources represent an important problem in terms of providing such resources for emergency situations. In particular, it is worthy of special mention that coactions by local people, enterprises and administrative offices have fulfilled their function in terms of enhancing proper management and preserving a

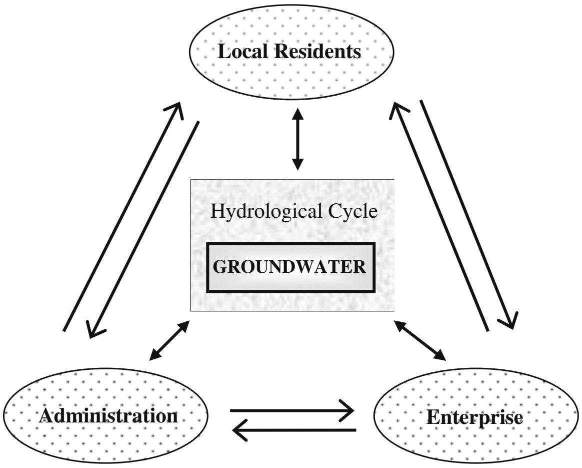


**Fig. 6** A concept for the sustainable management of groundwater resources based on coactions of three parties

better environment for groundwater. Figure 6 presents a concept for the sustainable management of groundwater resources based on coactions of the three parties mentioned above. Meanwhile, the need for a re-evaluation of groundwater as a vital resource has recently become more important from the view point of its indispensable role in the hydrological cycle. An administrative body has also driven forward the actual enforcement of policy concerning the conservation of groundwater resources and the establishment of a symbiotic water environment.

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# Climate Change and Groundwater

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## Abstract

Human civilisations have for millennia depended on the stability of groundwater resources to survive dry or unreliable climates. While groundwater supplies are buffered against short-term effects of climate variability, they can be impacted over longer time frames through changes in rainfall, temperature, snowfall, melting of glaciers and permafrost and vegetation and land-use changes. Groundwater provides an archive of past climate variation by recording changes in recharge amount or the chemical and isotopic evolutionary history of a groundwater system. For example, in the Sahara desert of North Africa, radiocarbon dating of groundwater shows that a highly arid climate prevailed during the last ice age followed by more humid conditions up until approximately 4000 years ago. In northern America and Europe, massive meltwater recharge of aquifers that occurred as a result of the same ice age approximately 15,000–20,000 years ago has left distinctive stable isotope signatures that remain today. The groundwater response to future climate change will be exacerbated by the heavy reliance that present day societies continue to place on groundwater, and the extensive modifications we have made to natural hydrological regimes. Models of groundwater response to climate change predict both increases and decreases in groundwater recharge and groundwater quality. Outcomes will be dependent on geographic location, and hydrological, biological and behavioural feedback mechanisms as natural systems and human civilisations struggle to cope with both climate change and our increasing demand for water.

## Keywords

Groundwater resources • Climate change • Palaeoclimate • Groundwater dating

## Introduction

Leonardo da Vinci said "*Water is the driving force of all nature*". Humans and other species have always used groundwater as a buffer against the effect of variable climates on water supplies, relying on springs and groundwater-fed streams for drinking water and on the

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animals and plants they attract for food. Civilisations have flourished with the development of reliable water supplies and then collapsed when that water supply has declined (Fetter, 1994). Aboriginal people in the arid and semi-arid Australian interior were using groundwater in caves 22,000 years ago. These people were highly dependent on native wells, springs and groundwater-fed lagoons (Bandler, 1995). Rural populations around the world have sourced their drinking water from wells and many towns and cities have been built around springs. Early Greek settlements were often built around karst springs and mythology says that Romulus and Remus founded Rome on springs along the Tiber River. As population density has grown, groundwater resources have increasingly been harnessed to supply reliable and clean drinking water to towns and cities around the world. Approximately 1.5 billion people now depend upon groundwater for their drinking water supply (UNEP, 2002) and combined with agricultural water use the amount of groundwater withdrawn annually is roughly estimated at 600–700 km$^3$, representing about 20% of global water withdrawals (WMO, 1997).

Both groundwater usage and its natural replenishment processes occur more slowly than short-term variations in climate, such as the changing seasons and natural cycles of storms, floods, snowmelt and drought. Thus, groundwater provides a buffering effect in the hydrological cycle. This groundwater buffer has helped humanity to maintain stable water supplies in a constantly varying climate. Increasing dependence on groundwater and exploitation of it as a resource, now makes human civilisations vulnerable again as climate change potentially alters the renewal of this resource.

While groundwater, as a buffering water source, has helped humanity to maintain stable water supplies in a constantly varying climate, the future may present limits not seen in recorded history. Many of the once-reliable aquifers have already been greatly depleted, and dependence on and exploitation of groundwater continues to rise at a time when climate variation is expected to increase, potentially altering the renewal of this resource.

This chapter summarises recent research on linkages between climate and groundwater including anthropogenic effects, palaeoclimate and predictions of future impacts.

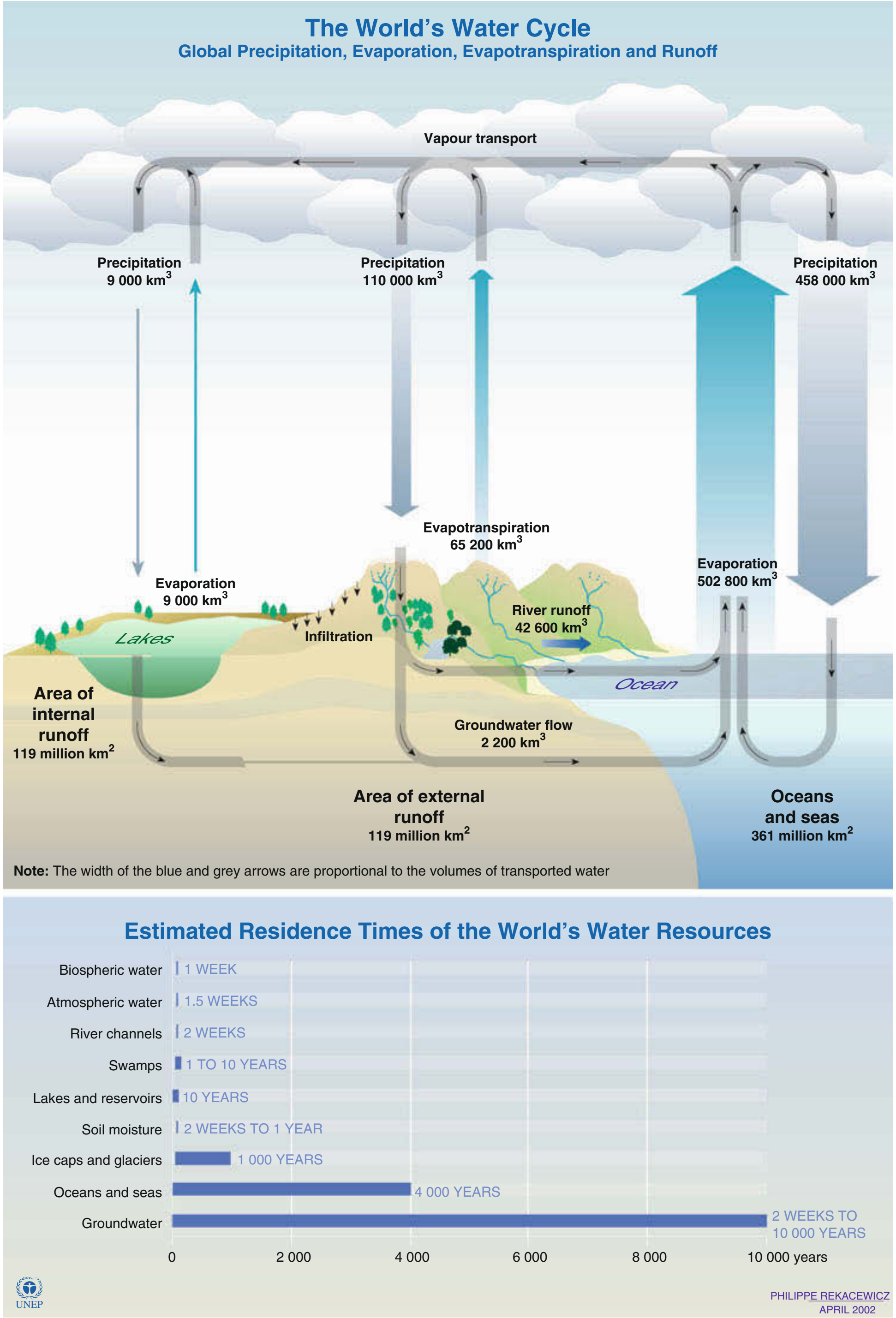
## Climate and Groundwater

Groundwater originates predominantly from evaporated ocean water which, after an average residence time of 8–9 days (Trenberth, 1998), returns to the Earth's surface as rain, hail or snow (Fig. 1). Some of the precipitation infiltrates into the ground and what is not evaporated from the surface, transpired by plants, or conveyed to surface water can saturate the pore spaces within rock and soil as groundwater. A layer of permeable rock or sediment that transmits groundwater is called an aquifer. Approximately 4% of the Earth's water is groundwater as compared to less than 1% found in fresh surface waters (Freeze and Cherry, 1979).

The cycling of water on the ground surface and in the soil occurs over periods of months to years; however, water in groundwater aquifers may have residence times from tens of years to hundreds of thousands of years before it flows into the ocean or landlocked basins. There is nothing simple or predictable about these water fluxes as they are controlled by many factors including precipitation patterns and temperature, vegetation and land use, soils and geology as well as water use and diversion by humans.

Climate is the major factor driving temporal variability in groundwater recharge. The geological record shows that climate variability on long time scales far exceeds that seen from the last 100 years or so of modern records. The long-term geological record is essential for understanding the frequency of extreme events like severe droughts and floods and provides insights into climate cycles that may recur at multidecadal or sub-millennial time scales.

Early recognition of large-scale climate change came over 150 years ago when geologists noticed that landforms normally associated with glaciers were now located large distances away from ice fronts. The next 120 years of research pieced together the history of ice caps, sea levels, deserts, lakes and vegetation and how these were related to the large-scale drivers such as perturbations in Earth's orbital parameters. It is known that the last 2.5 million years of Earth history are dominantly in glacial mode, with relatively short punctuations of 10,000 years or so of warm periods like the present. We also know that solar variability, volcanic



Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational, Scientific and Cultural Organisation (UNESCO, Paris), 1999; Max Planck, Institute for Meteorology, Hamburg, 1994; Freeze, Allen, John, Cherry, *Groundwater*, Prentice-Hall: Engle wood Cliffs NJ, 1979.

**Fig. 1** The world's water cycle: schematic and residence time. Drawn by Philippe Rekacewicz (Source: UNEP/GRID-Arendal. 2002. World's water cycle: schematic and residence time. UNEP/GRID-Arendal Maps and Graphics Library. Available at: http://maps.grida.no/go/graphic/world_s_water_cycle_schematic_and_residence_time. Accessed December 10, 2010) eruptions and phenomena like the El Niño Southern Oscillation drive short-term variability, and that some of this variability is translated through the oceans as part of a thermohaline circulation belt.

Research over the last 30 years has revolutionised how we view climate changes. In addition to understanding the long-term trends associated with Earth's orbital variation, we now recognise many changes appear to have occurred abruptly on geological time scales. Technological advances have enabled us to develop tightly constrained chronologies on climate effects that are global or regional. Many climate shifts have apparently taken place over a few years which suggests sudden changes in the driving forces of the Earth's climate system are not only possible, but might be more than the norm.

In the last 2000 years climate has appeared to be largely stable, with inter-annual climate variability in many parts of the world is driven by short-term cycles such as the El Niño Southern Oscillation, which results in swings in precipitation from above to below average in many regions in North and South America, Africa, India and Australia. In countries bounding the Indian Ocean and in SE Asia the Indian Ocean Dipole also affects rainfall and drought cycles. The Interdecadal Pacific Oscillation and Pacific Decadal Oscillation have been shown to generate dry-wet trends on multidecadal cycles affecting countries bounding both the North and the South Pacific.

Further to these natural drivers for climate variability, anthropogenic greenhouse gas emissions are resulting in rapid climate changes that are being observed in the present day and dominate the predicted global climate future (Fig. 2). The International Panel on Climate Change (IPCC, 2007, p.5) states that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level". These climate changes alter the global hydrological cycle affecting the balance between rainfall and evaporation, resulting in changes in groundwater recharge as well as the anthropogenic pressure on groundwater resources.

## How Changes in Weather and Climate May Impact Groundwater

Climate and weather patterns affect groundwater resources by altering recharge amounts and flow pathways in the hydrological cycle. Changing precipitation patterns, temperature and humidity affects the balance between surface water, evapotranspiration, soil water and groundwater in many ways as outlined below.

### Rainfall and Recharge – Amount, Intensity, Extremes

Groundwater recharge can be diffuse, occurring over a wide spatial area, or localised, resulting from seepage from river beds and lakes. Regardless of the recharge pathway, the aspect of weather that most directly affects groundwater recharge is precipitation. However, its not only the amount of precipitation that matters, groundwater recharge is also affected by the intensity of rainfall, whether it occurs in summer or winter and whether it falls as snow or rain.

Higher intensity rainfall leads to increased flooding and in alluvial floodplain aquifers this is generally the main source of recharge. In semi-arid or arid areas episodic flooding is the main contributor to groundwater. In areas, such as these, where the climate is characterised by cyclic periods of drought and floods, a change in the balance between wet and dry may affect groundwater recharge. In some areas if it rains more intensely the infiltration rate is limited by the soil's ability to absorb it, so diffuse groundwater recharge does not increase proportionally to increasing intensity.

Studies in the arid and semi-arid USA southwest (Scanlon et al., 2006) have shown that increased precipitation can lead to greater plant growth and plant water usage rather than an increase in recharge, and there is evidence from satellite-based measurements of vegetation productivity to suggest that this may be occurring in desert areas globally. Scanlon et al. (2006) reviewed a large number of studies of recharge in naturally vegetated areas and found that an average of 3% of precipitation was converted to recharge. In irrigated areas, 15% of combined precipitation and irrigation was found to be recharged. Where surface water is used for irrigation purposes, water tables are more likely to rise closer to the surface. However, where groundwater is pumped for irrigation the drawdown from the

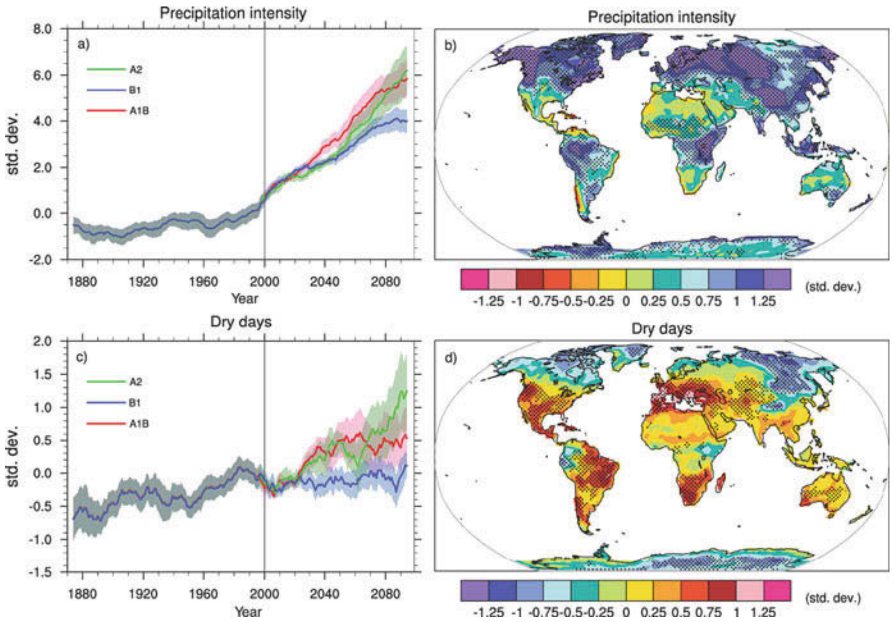


**Fig. 2** Globally averaged measured and modelled changes in precipitation intensity (**a**) and maximum consecutive dry days (**c**); and the modelled change between 1980–1999 and 2080–2099 in precipitation intensity (**b**) and maximum consecutive dry days (**d**) for the A1B scenario (IPCC 2007, figure 10.18, Source: http://www.ipcc.ch/graphics/ar4-wg1/jpg/fig-10-18.jpg)

pumping is generally greater than the recharge so water tables may become lower.

Aquifers in many arid areas receive little or no recharge at all. The use of chloride concentration profiles and groundwater dating tools such as $^{14}C$ has provided evidence that areas in the southwestern USA and in north Africa last experienced significant widespread recharge during the Pleistocene period (10,000–15,000 years ago) when the climate was more humid (Scanlon et al., 2006). During the following Holocene period, recharge only occurred beneath river channels and freshwater lenses can still be found beneath ancient buried river channels.

If the climate changes from humid to arid, the streams can change from gaining systems (i.e. groundwater fed) to losing. Where this reversal in hydraulic gradient occurs, it is likely to have adverse affects on water resource allocations for the area.

## Temperature and Evapotranspiration

Groundwater responses to changes in temperature and evapotranspiration are more subtle than the response to rainfall. Direct evapotranspiration losses from groundwater may occur where the water table is shallow, particularly in marshes or wetlands, making these groundwater-dependent ecosystems vulnerable to the effects of climate variability. However, in most cases temperature effects on groundwater are indirect, with increased temperature leading to higher potential evapotranspiration, intercepting water as it infiltrates and recycling it back into the atmosphere at the expense of recharge. Conversely, decreases in temperature reduce potential evapotranspiration and potentially increase recharge.

Evapotranspiration rates are also affected by rainfall patterns and rainfall intensity, wind speed and cloud cover, as well as changes in vegetation; these feedback mechanisms may have counter-intuitive outcomes. For example, evapotranspiration rates are greater during low-intensity events, so an increase in storm intensity might lead to lower losses even if potential evapotranspiration increases (Cartwright and Simmons, 2008).

Apart from influencing evapotranspiration rates, a key effect of temperature in relation to groundwater recharge is in determining whether it snows or rains.

## Snowfall and Snowmelt

When precipitation falls as snow rather than rain, the dynamics of recharge are very different. Because the snowpack builds up over the winter season, it stores water from many storms together. Snowmelt is highly effective in recharging groundwater as it provides a steady source of water for infiltration into the ground over a period of weeks to months. This may provide sufficient water to pass through the unsaturated zone and recharge deeper groundwater resources. When precipitation falls as rain rather than snow, then a higher proportion of surface runoff will be generated. Whether the net recharge to groundwater would be different for a particular catchment due to a change in the proportion of snow and rain is difficult to predict and depends on the geology of the catchment. A reduction in snow accumulation, raising of the snowline or decrease in the length of the snowmelt season may dramatically reduce recharge in mountain aquifers. However, runoff from mountainous regions also contributes to infiltration to alluvial aquifers at their base. Flood flows provide the bulk of recharge in such aquifers and an increase in the proportion of rain to snow storms may increase recharge in these cases.

In the western mountains region of the USA, stable isotopes in groundwater and precipitation have shown that snowmelt is the major contributor of groundwater recharge to the system (Earman et al., 2006), providing between 50 and 90%. However, the snow accumulation has declined in recent decades (Earman and Dettinger, 2008) replaced by increased rainfall, which is less effective at recharging groundwater. Modelling of the effects of climate change in Sierra Nevada predicts that snow water amount will have declined by 33–79% of historical levels by the end of the 21st century (Dettinger et al., 2004) resulting in significant changes to spatial distribution and amount of groundwater recharge.

### Permafrost and Glaciers

A more dramatic change in groundwater recharge conditions occurs during periods of glaciation or permafrost. During a period of glaciation for instance, most of the precipitation is in the form of snow and cooler temperatures result in permanent layers of ice or frozen soil which may form a barrier to recharge of any remaining surface water that occurs seasonally. Aquifers underlying shallow permafrost and glacial ice often receive little recharge with gaps in the recharge timeline noted in many locations during the last glaciation. Glacial meltwaters commonly lead to groundwater recharge at the base and foot of the glacier, and in some cases the overburden pressure of the thick ice accelerates recharge beneath (Grasby and Chen, 2005). Rising temperatures in the future may lead to melting of permafrost, such as those currently covering large areas in Siberia and Alaska, resulting in recharge to aquifers which have received none for thousands of years.

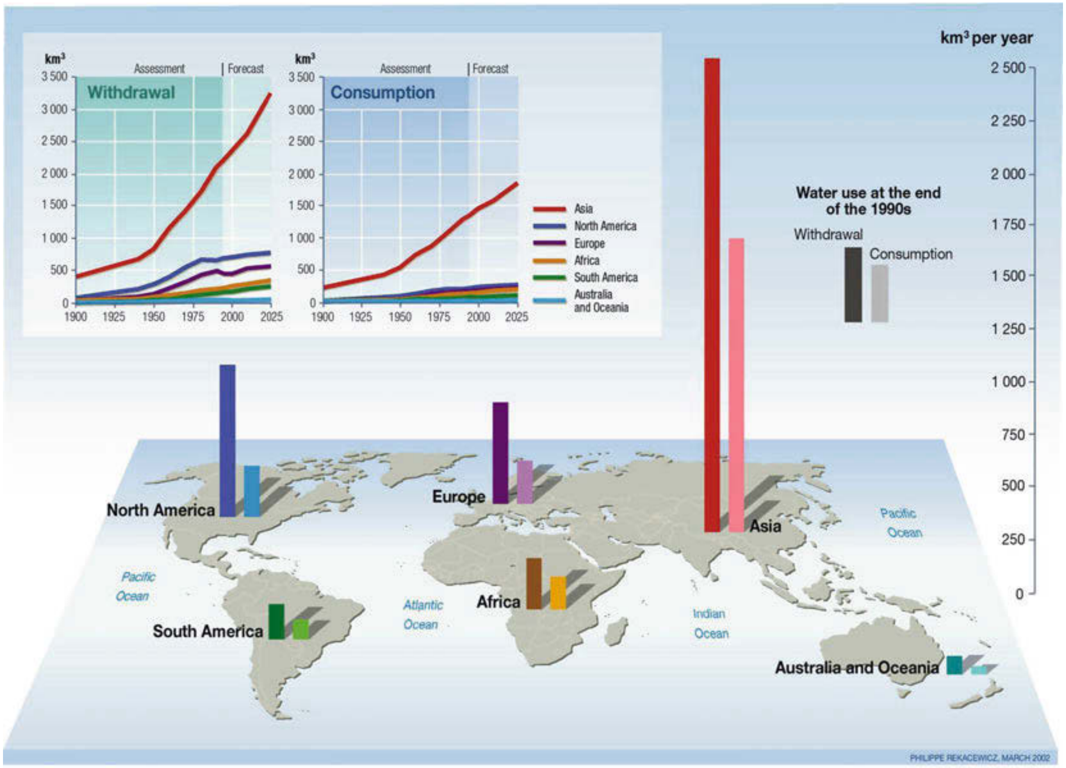
## Anthropogenic Effects and Feedback Mechanisms

In addition to the climate impacts that control groundwater recharge and availability, human land use and water usage have a dramatic effect on groundwater resources. In 2000 groundwater supplied 18.25% of water withdrawals and 48% of drinking water (World Water Assessment Programme, 2009). Human water demand is increasing at an accelerated rate with global water withdrawals projected to increase by 10–12% every decade (Shiklomanov and Rodda, 2004; Fig. 3). In many areas this additional water demand is being supplied by groundwater.

Human behaviour in response to changes in weather or climate may further affect groundwater resources. If, as a result of a decrease in rainfall or an increase in temperature, groundwater pumping is increased to meet irrigation water needs, the groundwater resource is impacted by both reduced recharge and increased extraction. Similarly, if a change in climate makes one type of agriculture unsustainable then any change in land use will likely affect recharge – either positively or negatively.

Natural vegetation patterns and forest or grass fire frequency and intensity are also affected by climate and in turn either gradually or dramatically alter the vegetation coverage or make soils water repellent in the case of fires. These changes in vegetation affect groundwater recharge by changing the amount of precipitation that is intercepted and how much is transpired and by altering the soil structure and organic matter content.

Groundwater levels also have a direct feedback to regional climate. Wherever groundwater discharge sustains river levels, wetlands and lakes, or where soil moisture levels are replenished from below by groundwater, evaporation and transpiration cycle moisture back into the atmosphere to rejoin the climate system. In areas with very shallow water tables there is typically enough moisture to sustain this cycling; conversely where water tables are deep groundwater is disconnected from the atmosphere. However, in the



Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational,Scientific and Cultural Organisation (UNESCO, Paris), 1999; *World Resources 2000-2001, People and Ecosystems: The Fraying Web of Life*, World Resources Institute (WRI), Washington DC, 2000; Paul Harrison and Fred Pearce, *AAAS Atlas of Population 2001*, American Association for the Advancement of Science, University of California Press, Berkeley.

**Fig. 3** Water withdrawal and consumption: the big gap. Drawn by Philippe Rekacewicz (Source: UNEP/GRID-Arendal. Water withdrawal and consumption: the big gap. UNEP/GRID-Arendal Maps and Graphics Library. 2009. Available at: http://maps.grida.no/go/graphic/water-withdrawal-and-consumption-the-big-gap. Accessed December 10, 2010)

zone between, which has been found to be 2–5 m deep in the southern Great Plains of the USA (Maxwell and Kollet, 2008), the balance between precipitation and evapotranspiration controls the availability of water for recycling to the atmosphere. This is the zone where changes in recharge may feedback to alter climate. Modelling of the 1998 drought in Oklahoma and Texas, USA, (Hong and Kalnay, 2000) showed that whilst the onset of the drought was driven by sea surface temperature anomalies associated with the El Niño Southern Oscillation, the drought was sustained by a positive feedback mechanism where low rainfall reduced soil moisture levels resulting in less recycling of moisture to the atmosphere for future precipitation.

Climate change can also influence the groundwater chemistry. Just as increasing $CO_2$ emissions affect the atmosphere, they also have the potential to impact shallow groundwater chemistry. A 15-year study by Macpherson et al. (2008) of a mid-continental North American grassland found that the partial pressure of $CO_2$ increased by 20% from 1991 to 2005. They found that the carbonate minerals in this shallow aquifer system were being dissolved in response to a lowered groundwater pH from the increasing $CO_2$. The long-term increase in $CO_2$ concentration in the shallow groundwater was found to be similar to, but greater than, atmospheric $CO_2$. Studies such as these highlight the importance of considering the connectivity of the various components of the hydrological cycle. Rising $CO_2$ emissions are not only going to impact climatic conditions but may well influence the water quality of shallow groundwater systems.

## Evidence of Past Climate in Groundwater Records

As groundwater infiltrates and migrates through an aquifer, hundreds to millions of years may elapse before it discharges at the Earth's surface. Under favourable conditions, information about the nature and timing of historical recharge can be extracted and interpreted to give insight into past climates. When seen as information sources, groundwater systems are considered low-resolution archives, in contrast to other high-resolution archives such as ice cores or corals that contain information on finer time scales. The information contained within an aquifer contains a more regional perspective of climatic conditions for the studied area. Application of age tracers to hydrological studies is widespread in scientific literature, while studies that directly link the groundwater age with palaeoclimatic information are scarce. However, with direct or indirect palaeohydrogeological methods we can sometimes reconstruct the sequence of events or feedbacks between climate and groundwater.

## Groundwater Tracers to Indicate Past Climate

In order to obtain palaeoclimatic information from groundwater we need to deduce its "age". The time elapsed between when the water entered the saturated zone and some later date of interest, such as upon extraction of sample, is generally referred to as "residence time". Groundwater residence times may be estimated using physical or chemical methods. The physical approach uses Darcy's law to calculate the average linear velocity, and consequently the relationship between groundwater age and distance from the recharge point, where the hydraulic conductivity, gradient and porosity are known. The major downfall of using this method in isolation is that the hydraulic conductivities and porosities of an aquifer are often poorly defined at the scale of interest. These parameters are often extrapolated over extensive geographic areas and do not account for geological complexities such as faulting. When extrapolated over palaeo time scales, the Darcy's law method yields residence times that typically include large uncertainty.

Chemical methods can also be used to determine groundwater age using radioactive decay of naturally occurring radioisotopes, concentrations of conservative elements and concentrations of certain radioisotopes or molecules linked to specific events such as nuclear weapons testing, widespread release of CFCs and $SF_6$ gases to the atmosphere or local industrial processes. Other less direct chemical methods include: stable isotopic signatures of water molecule isotopes, the ratios between radiogenic and stable isotopes, and noble gas concentrations that can be linked to recharge temperatures occurring during past climatic events (Stute et al., 1995). Because past climates influenced the water stable isotope ($\delta^2$H and $\delta^{18}$O) signature of rainfall, the differences between modern and past water isotopic ratios can be linked to specific climatic events such as the melting of an ice sheet cover, change in marine currents, or generalised increases or decreases of surface temperatures. The use of chemical methods also results in errors because they do not account for all processes such as dispersion or mixing. The effect of dispersion in particular reduces the variability of any climatic proxy in the recharged water and effectively reduces its temporal resolution (Davison and Airey, 1982). However, major advantages of using chemical methods are that parameters result from the integration of all variables influencing the hydrology of the region (Love et al., 1994). The residence times calculated from both approaches can be substantially different, yet most studies generally focus on only one. The use of several age tracers, detailed hydrogeological assessment and the combination of these with reactive transport modelling offers a more robust approach to any groundwater investigation (Bethke and Johnson, 2008; Phillips and Castro, 2004).

### Naturally Occurring Radioisotopes as Age Tracers

Use of radioisotope tracers such as $^{36}$Cl, $^{32}$Si, $^{14}$C and $^{129}$I has been the predominant method (Fig. 4) of dating groundwater in reported studies. This method calculates age by using an estimate of the concentration of the radioactive element at the time of infiltration, corrected for the known decay of the radioisotope. As an example, if there were 1000 atoms/L of $^{36}$Cl in freshly recharged water and a sample of deeper groundwater had 500 atoms/L then we would estimate that one half-life had passed since recharge (one half-life = 301,000 years for $^{36}$Cl). New advances in accelerator

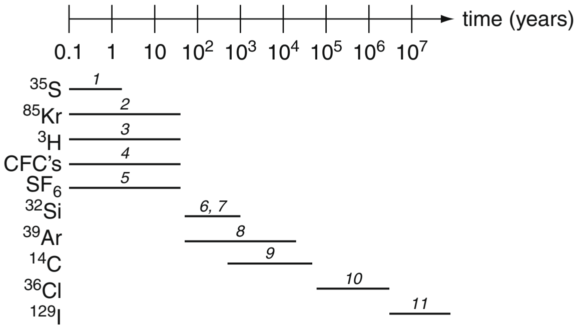


**Fig. 4** Age dating ranges for commonly used radioisotope and anthropogenic tracers. Key bibliography: *1* Sueker et al. (1999); *2* Rozanski and Florkowski (1979); *3* Kaufman and Libby (1954); *4* Busenberg and Plummer (1992); *5* Busenberg and Plummer (2000); *6* Lal et al. (1970); *7* Morgenstern (2000); *8* Loosli et al. (2000); *9* Clark and Fritz (1997); *10* Phillips (2000); *11* Fabryka-Martin et al. (1985)

mass spectrometry (AMS) have led to the development of more isotopic age tracers, enabling the extension of these types of studies to a wide number of aquifer systems (Collon et al., 2000; Fehn et al., 2000). Currently, the techniques used to apply these isotope methods are far from routine. The elemental concentrations or radioactivity levels of some of the radioisotope tracers, $^{85}$Kr, $^{39}$Ar, $^{129}$I, for example, are quite low, requiring the extraction of tiny amounts of the elements of interest from water samples of up to several thousand litres. These sample sizes can only be achieved from high yielding wells and aquifers, which may be challenging in arid zones or poor aquifers.

A key consideration when using isotopes is that interaction between groundwater and aquifer rock or soil during recharge and flow can increase or decrease the tracer concentration. Calculations or models are used to compensate for this effect; however, there typically remains substantial uncertainty because the rate of interactions can vary widely as groundwater moves through different types of geology. Furthermore, these tracers have an "age range" (indicated in Fig. 4) that has to be appropriately chosen to fit study conditions. For example, the use of a tracer capable of determining ages of a million years would not be appropriate in assessing a shallow alluvial aquifer where young ages would be expected. All of these factors must be carefully considered when using age tracers in hydrogeological studies and should be combined with a detailed understanding of the geology of the area. The particular advantages of the most popular age tracers have been discussed extensively in the scientific literature (among many others; Clark and Fritz, 1997; Phillips and Castro, 2004; Kazemi et al., 2006; Bethke and Johnson, 2008).

## Stable Anthropogenic Age Tracers

Global industrialisation, particularly since the 1930s, has been accompanied by the release of certain industrial chemicals that are resistant to degradation and would otherwise be absent, or very rare, in the natural environment (Plummer, 2005). These chemicals can be used as tracers of young waters where their concentrations in the environment over time are well known. The best examples are chlorofluorocarbons (CFCs) which provide a signature related to the last half of the 1900s when they were widely used in refrigeration until their damage to the ozone layer led to international treaties to phase out their use (Montreal Protocol). Now that the atmospheric concentrations of CFCs have started to decrease (Fig. 5) their usefulness in tracer studies is diminishing (Plummer, 2005). Another mostly industrial gas, with similar dating capabilities to CFCs, is sulphur hexafluoride (SF$_6$). Widely used in the electrical industry, its atmospheric concentration is continuing to increase despite being one of the most potent greenhouse gases. Natural production has also been reported in igneous and volcanic areas, so separating natural from anthropogenic sources is vital for its use as age tracer (Busenberg and Plummer, 2000).

## Other Indirect Tracers of Age or Palaeoclimate

In some cases isotopes or elements that are not generally used as age tracers can be used to estimate age if they show differences (signatures) that can be attributed to a major climatic event. This approach has been illustrated with an example from the last ice age, when kilometre-thick continental ice sheets occurred in North America and Europe. The ice had been accumulated under colder conditions and therefore their water stable isotope ratios ($\delta^2$H and $\delta^{18}$O) were more depleted than those of modern rainfall (Clark and Fritz, 1997). During the ice age, water with a particular isotopic signature entered underground aquifers. In some cases, the pressure of the thick ice caused vast amounts of recharge to occur even to the extent of changing regional groundwater flow directions (Grasby and Chen, 2005; Grasby et al., 2000; McIntosh and Walter, 2005). Groundwater extracted today across parts of Europe and North America

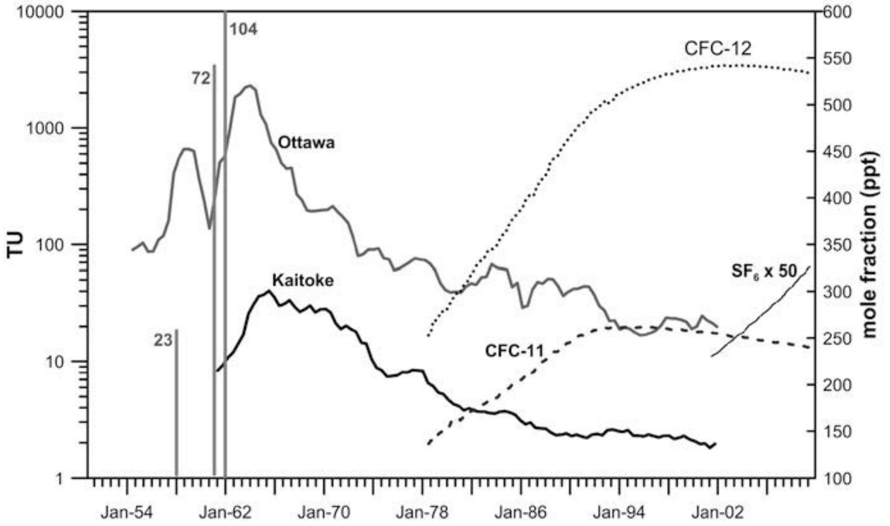


**Fig. 5** Five-point running average of tritium concentrations in rainfall at Kaitoke (New Zealand) and Ottawa (Canada) and CFC-11, CFC-12 and $SF_6$ concentrations at Tasmania, Australia. The *vertical lines* represent maximum $^3H$ release to atmosphere from thermonuclear weapon testing. The numbers beside the lines are terabecquerels of $^3H$ released (GNIP-data; Gonfiantini 1996; Rath 1988). SF6, CFC-11 and CFC-12 (Source: http://agage.eas.gatech.edu/data.htm, accessed on 9/12/2010)

preserves this distinctive water stable isotope signature indicating its Last Glacial Maximum origin and therefore a late Pleistocene age (∼20 ka). In more temperate areas, groundwater recharged during wetter or dryer climatic conditions can also carry distinctive stable isotope signatures (i.e. Jirákova et al., 2009; Galego Fernandes and Carreira, 2008). The age of this groundwater can in some cases be estimated when compared to other climatic proxies such as pollen abundances or shore evolution in lacustrine sediments.

Similarly, the temperature solubility dependence of noble gases (neon, argon, krypton and xenon) can be used to estimate palaeotemperature of groundwater during recharge (Kipfer et al., 2002). The temperatures deduced from the noble gas thermometer can have gaps in areas where recharge has not been continuous, particularly areas affected by glaciation or desertification. The best temperature records can generally be obtained at low latitudes where uninterrupted groundwater recharge is more likely (Kipfer et al., 2002). Direct determination of groundwater temperatures and their comparison over time can also provide insights into subsurface warming and particularly reflect land practice changes as well as global trends (Kooi, 2008).

Noble gas stable isotopes like $^4$He and $^{21}$Ne can also be used as age tracers. The chemically inert character of these elements means that theoretically they can accumulate in the groundwater with increasing concentrations correlated to longer residence times (Stute and Talma, 1998; Castro et al., 2000). These are produced by radiogenic processes in the subsurface. While $^{21}$Ne requires sufficiently high uranium concentrations in the host rocks to accumulate in sufficient quantities, helium can generally accumulate in the groundwater to measurable concentrations for noble gas mass spectrometry. The use of $^4$He to estimate groundwater residence times needs to account for any sources of helium in the groundwater such as excess air generally trapped in air bubbles during groundwater table fluctuations, decay of natural or anthropogenic $^3$H (producing tritiogenic $^3$He), the decay of natural U and Th, reactions with $^6$Li producing tritiogenic $^3$He and mantle contributions to both $^3$He and $^4$He. Apart from the sources of helium, a number of assumptions or models need to be considered to understand the transport within the aquifer and to account for helium dispersion. Due to all these factors $^4$He has mostly been applied in well-characterised aquifer systems and compared to other tracers to assess its validity.

## Tritium and Carbon-14 – The Most Popular Age Tracers

Of all the groundwater age tracers, tritium ($^3$H) and carbon-14 ($^{14}$C) have been most widely used in hydrologic studies, with $^3$H used to assess modern groundwater (up to ~70 a), and $^{14}C$ used for older groundwater (up to ~40,000 a). Their use as age tracers was led by Noble laureate Willard Frank Libby (Kaufman and Libby, 1954; Libby, 1967). The relative abundance of these elements in water has allowed for their separation from small volumes of water and their measurement using traditional beta counters. In recent years, wider access to AMS has stimulated a renaissance in the use of $^{14}C$ by pushing the datable range back whilst increasing precision and decreasing the required sample volumes. Both isotopes cover highly useful residence times for groundwaters. Tritium can record ages spanning from the first post-war nuclear tests and $^{14}C$ covers the Holocene and Late Pleistocene including some of the most relevant climatic events in human history such us the latest interglacial period and its transition to the last glacial period.

Tritium is naturally produced in the atmosphere by cosmic-ray spallation of nitrogen, with a half-life of 12.3 years. However, the artificial $^{3}H$ generated as a consequence of nuclear weapons testing introduced concentrations many thousands of times above natural levels reaching its highest peak in the mid-1960s. This anthropogenic $^{3}H$ signal has allowed it to be used to date young groundwater. As most nuclear testing took place in the northern hemisphere, tritium activities reached their highest levels there in 1963 (Fig. 5). The slow mixing along the equator and small-scale testing in the southern hemisphere meant the tritium peaks were much lower in southern latitudes, and now have returned to their natural background levels. Today, even in the northern hemisphere tritium concentrations have almost returned to their natural levels. Recent improvements in $^{3}H$ detection levels, and the increasing use of the $^{3}H/^{3}He$ ratio, make it possible to continue using $^{3}H$ in groundwater studies, without the anthropogenic interference.

$^{14}C$ applications have revolutionised the fields of Holocene–late Pleistocene palaeoclimate and archaeological research. $^{14}C$ is naturally produced in the atmosphere by low-energy cosmic-ray neutron reactions with nitrogen. The abundance of nitrogen in the atmosphere favours the production of $^{14}C$, being the most abundantly produced cosmogenic radionuclide. $^{14}C$ is quickly oxidised to $^{14}CO_2$ and mixes in all the major carbon reservoirs on Earth. Nuclear weapons testing also contributed to a peak, generally termed the "bomb pulse", that indirectly can be of use in dating recently recharged waters (post-1950). The bomb pulse signature in the atmosphere is at present reaching pre-1950s levels. This anthropogenic peak is not relevant for older groundwater. Radiocarbon measurements are generally reported in pMC "percent Modern Carbon" which represents $^{14}C$ activities prior to bomb testing. As $^{14}C$ is incorporated in both organic and inorganic fractions, both can be used as age tracers. The dissolved organic carbon (DOC) fractions (i.e. humic and fulvic acids) can be dated (Aravena and Wassenaar, 1993) but more commonly the dissolved inorganic fraction (i.e. the sum of all inorganic carbon sources such as carbon dioxide, bicarbonate and carbonate) is dated in the groundwater.

The $^{14}C$ activity can be easily transformed into an age using the $^{14}C$ decay equation (Clark and Fritz, 1997). The age calculated is referred to as an uncorrected age, as there is no consideration of any additional chemical or physical processes that may have influenced the water in the aquifer. A number of geochemical corrections have been developed to account for these water–rock interaction processes which result in carbon loss and gain. The appropriate selection and use of a correction model will depend on the available data and the geological setting of the studied area (Fontes and Garnier, 1979; Pearson, 1965; Plummer et al., 1994; Clark and Fritz, 1997).

## Palaeohydrology Case Studies

Most age tracer studies are applied to small geographic areas or specific aquifers because it is on these scales that the necessary sample data are typically gathered. However, when local studies are combined in a large system like the Sahara (N Africa) insights can be gained at continental or global scales. Two examples are presented below that use applied palaeohydrological techniques in large aquifer systems to identify past climatic changes.

### Groundwater and Past Climates in the Sahara Desert

The northern Sahara sedimentary basin covers more than 780,000 km$^2$. While recharge in the modern hyper-arid conditions is small or insignificant, the abundant groundwater found in the area reveals that the basin must have been subjected to wetter periods in the past, implying that groundwater was recharged under different climatic conditions.

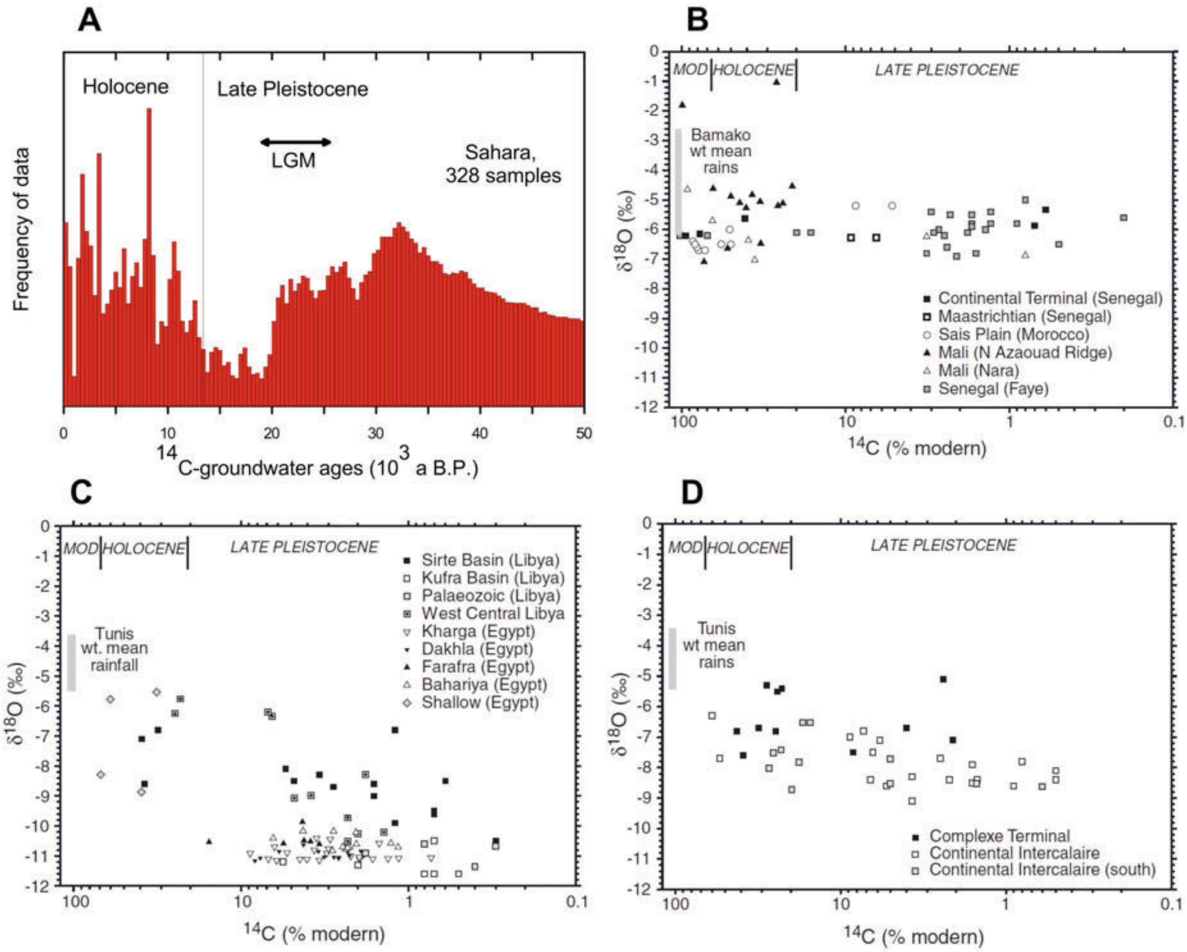


**Fig. 6** (**a**) Frequency distribution of apparent (non-corrected) $^{14}$C ages of Saharan groundwaters (redrawn from Sonntag et al., 1980 with kind permission from Radiocarbon); (**b**, **c**, **d**) The change in $\delta^{18}$O versus pmC during the Holocene and late Pleistocene for a SW–NE transect from Senegal to Egypt (from Edmunds et al., 2004, figure 2a, d and e, with kind permission from Springer Science+Business Media B.V.)

Sonntag et al. (1980) compiled over 300 $^{14}$C groundwater results covering the Sahara. The distribution of ages showed particular gaps or abundances that can be correlated to broad climatic shifts in the Holocene and late Pleistocene (Fig. 6). Additional data from Guendouz et al. (2003) and Edmunds et al. (2004) show no samples in the range of 5–15 pMC broadly coinciding with the Last Glacial Maximum between 23,000 and 18,000 years ago. The Holocene period shows a wide scatter of age frequencies that coincide with the intercalation of short millennial scale wet/dry phases, with intense wet periods (i.e. from 11 to 5 ka) before the onset of the predominantly dry weather we observe today at about 4 ka. The age distribution of groundwater across the Sahara reveals the existence of periods with less $^{14}$C data, coinciding with times of reduced recharge or dryer conditions. The general chronology interpreted from groundwater coincides with data deduced from sedimentological, palynological and microfossil records from cores in lakes across Africa (Gasse, 2000) providing additional confirmation of past climatic phases in the Sahara.

Further information for the Sahara can be obtained when the chronological data are combined with water stable isotopes and noble gas recharge temperatures from groundwater. A general trend is observed from west to east in the $\delta^{18}$O composition of later Pleistocene palaeowaters (Fig. 6b), with more depleted values towards the east with respect to modern values. This is interpreted as an overall continental effect

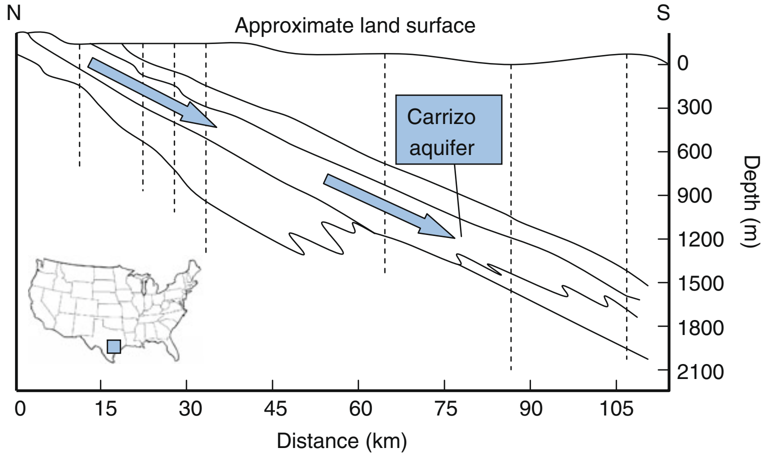


**Fig. 7** NW–SE schematic cross section of El Carrizo Aquifer showing the general water flow direction (after Castro et al., 2000, figure 1, with kind permission from Elsevier)

where Atlantic moisture sources would have become isotopically lighter in its trajectory from West to East. Also, in order to have groundwater recharge there must have been abundant rainfall as compared to today's dry Sahara; this is also consistent with the generally more depleted isotopic values found in the late Pleistocene groundwater. Edmunds et al. (2004) link these trends to a shift south of the subtropical jet stream and a weakening of the south-west monsoon during the late Pleistocene. Noble gas palaeotemperatures from different areas in North and South Africa point to ~5°C cooler temperatures for groundwater during the Last Glacial Maximum with 1–2°C lower temperatures towards the centre of the continent (Loosli et al., 1998). The combination of the groundwater $^{14}$C chronological framework with water stable isotopes and noble gas palaeotemperatures provides quantitative changes in past temperature as well as evidence and timing of climatic changes across the Sahara.

## Palaeorecharge in the Carrizo Aquifer, Texas, USA

The "Carrizos" (Spanish for reeds) have now long gone in many areas as natural surface springs started to dry out in late 1920s (Pearson and White, 1967). From 1920 to 1970 groundwater levels in some areas have declined in excess of 70 m, with most counties parallel to the Texan coast relying on this aquifer for water supply either totally or for major agricultural developments such as the Winter Garden region. The social and economic importance of this water resource has prompted numerous geochemical and hydrogeological studies including age tracer studies comparing several methods in an effort to better manage groundwater resources.

The Carrizo sand outcrops at the surface in a band nearly parallel to the Gulf Coast of Texas (Fig. 7). The aquifer dips down towards the southeast and is confined between shale layers. The composition of this mostly unconsolidated and uniform aquifer consists of fine to medium-grained quartz sand with minor amounts of clay, lignite (organic matter), calcite and pyrite (Pearson and White, 1967). Rainfall recharges the aquifer at the outcrop area and groundwater flows towards the southeast with freshwaters detected at depths of up 1500 m but with a tendency to higher salinities along the flow path.

Early applications of $^{14}$C in the area showed a consistent southeast increase in age with distance from the outcropping Carrizo sand (Pearson and White, 1967). Further $^{14}$C data and residence times calculated from hydrological models all coincide with chronologies obtained from $^{4}$He dating (Castro et al., 2000). This has allowed a chemical tracer ($^{4}$He) to extend the general chronology beyond the $^{14}$C limits. The combination of noble gas temperatures and the different chronology frameworks have provided a general palaeoclimatic understanding of the Carrizo recharge area differentiating three main periods (Fig. 8): (1) a shift from modern mean temperatures of 20.6 ± 0.6°C towards lower temperatures in the Holocene–late Pleistocene, (2) minimum temperatures between 15.4 and 16.2°C coinciding with the Last Glacial Maximum and (3) warmer temperature between 30 and 150 ka with older recharge temperatures similar to modern conditions.

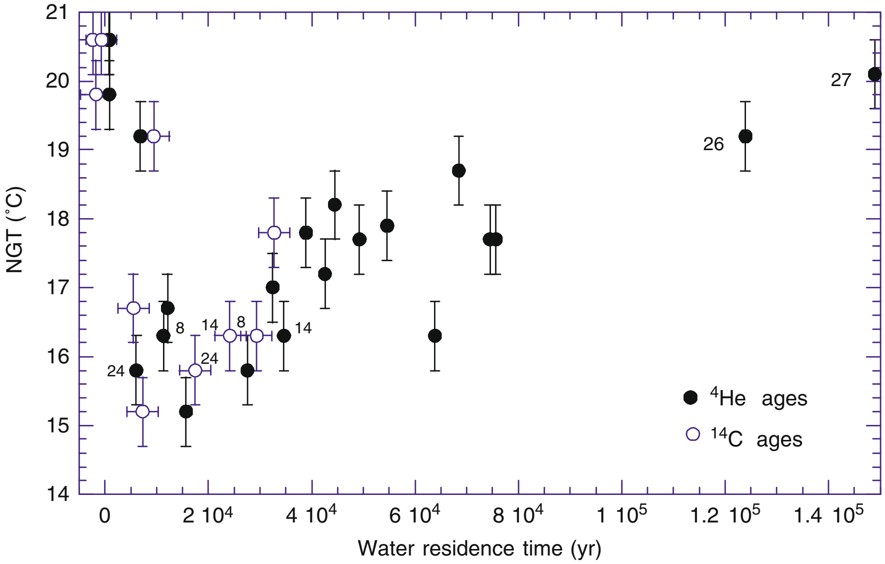


**Fig. 8** Noble gas temperatures evolution against $^4$He and $^{14}$C water residence times from the mid-Pleistocene to present (from Castro et al., 2000, figure 13a, with kind permission from Elsevier)

## Predictions of Climate Change Effects on Groundwater

### Global Predictions of Groundwater Impacts

Potential impacts on groundwater from climate change has been the subject of an increasing number of studies in recent years as improvements have been made in global climate models. These studies have considered potential impacts such as changes to groundwater recharge rates, aquifer levels and water supplies, as well as impacts to water quality such as the potential for seawater intrusion into freshwater aquifers.

In 2007, the Intergovernmental Panel on Climate Change (IPCC) published a set of model outcomes predicting changes in groundwater recharge on the global scale considering two different greenhouse gas emission scenarios and using two different global climate change models. The resulting outcomes (Fig. 9) estimated groundwater recharge amounts in the 2050s as compared to a 1961–1990 baseline. The model results suggest recharge deficits of more than 70% in north-eastern Brazil, south-western Africa and the southern rim of the Mediterranean Sea, with smaller deficits indicated in other locations particularly those in the mid-latitude regions. In contrast, groundwater recharge was predicted to increase by more than 30% in the Sahel, the Near East, northern China, Siberia and portions of the western USA (IPCC, 2007).

The two emission scenarios used in the above study (A2 and B2) both assume continuous population growth with the A2 scenario having a greater growth rate compared to the B2 scenario. These two scenarios are part of a group of six greenhouse gas emission scenario families designated A1FI, A1B, A1T, A2, B1 and B2 in IPCC reports. The scenario families represent various demographic and societal projections affecting rates and amounts of greenhouse gas emissions. For example, the set of A1 scenarios all anticipate a global population peak of 9 billion in 2050, with the A1FI scenarios emphasizing fossil fuel use, the A1T emphasizing new technologies replacing fossil fuels and the A1B considering a mixture of technologies. These scenario families, called SRES Scenarios, from the IPCC Special Report on Emission Scenarios (Nakićenović and Swart, 2000) have not been without controversy, but have provided a relatively uniform common set of starting points for numerous recent global circulation modelling efforts.

In addition to using multiple emission scenarios, studies on potential groundwater impacts make use of different global climate models such as the ECHAM4 and HadCM3 used in the above study. Global climate models continue to evolve in their ability to include a

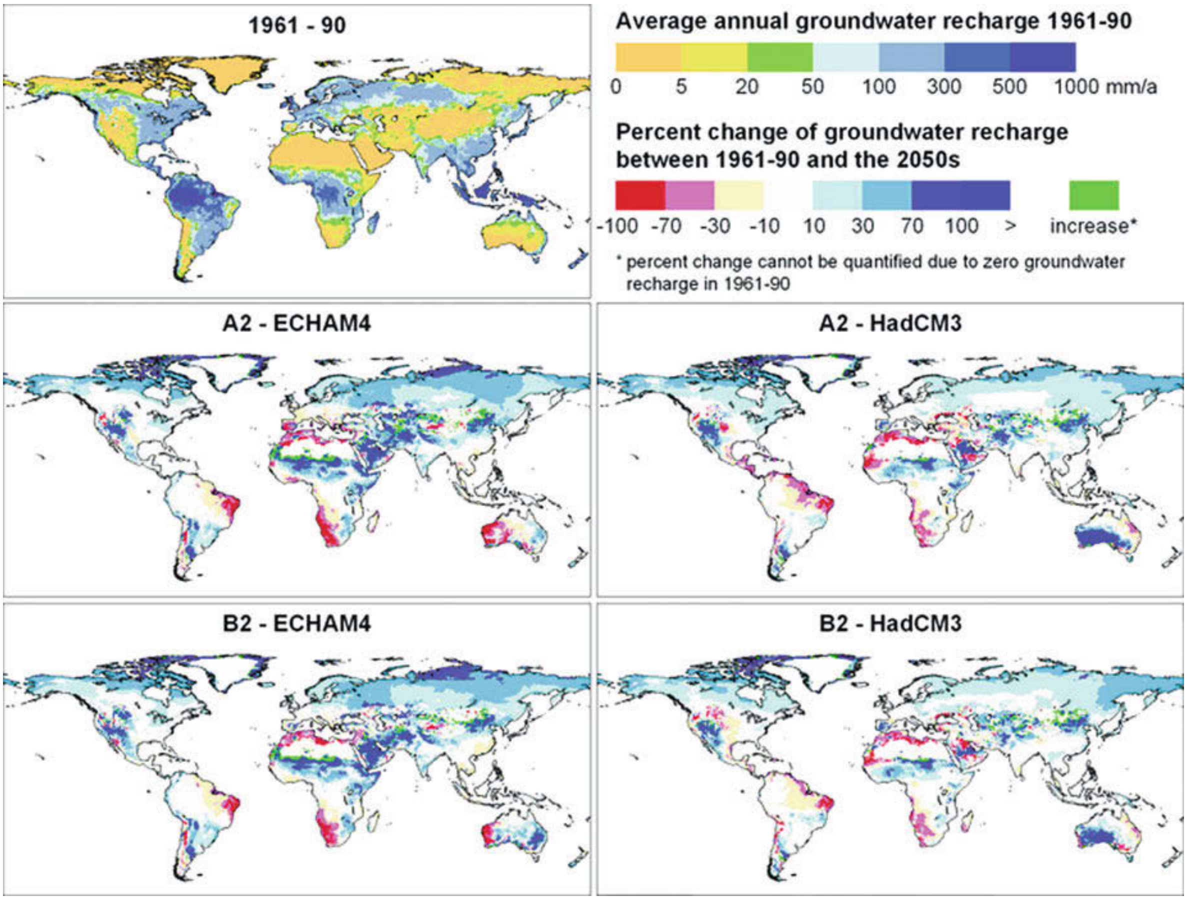


**Fig. 9** Simulated impact of climate change on long-term average annual diffuse groundwater recharge. Percentage changes in 30-year average groundwater recharge between the present day (1961–1990) and the 2050s (2041–2070), as computed by the global hydrological model WGHM, applying four different climate change scenarios (based on the ECHAM4 and HadCM3 climate models and the SRES A2 and B2 emission scenarios) (Döll and Flörke 2005; IPCC 2007). From http://www.ipcc.ch/publications_and_data/ar4/wg2/en/figure-3-5.html

greater number of, and more complex, physical processes. For example, the HadCM3 (*Hadley Centre Coupled Model, version 3)* couples atmospheric and ocean processes to improve the overall climate simulation. Over time, improvements in global climate models have provided outcomes on finer scales with the effect of making more information available on the regional, watershed or local scales typically used in most groundwater studies.

Despite improvements, global-scale models contain various levels of uncertainty as they simulate complex systems of air, water and land masses interacting with each other and with an increasing influence of human activity. The authors of the above study noted that the "difference between the results of the two climate models for the same emissions scenario are more significant than the differences between the two emissions scenarios" (Döll and Flörke, 2005) suggesting that there exists substantial potential for improving predictions through further model development and refinement.

Reducing uncertainty is a key focus of current modelling efforts. Typical of most recent efforts, the above study used available data, in this case 25 independent groundwater recharge estimates, from various global locations to calibrate or tune the hydrologic model component. The above study is typical in that simplifying assumptions were made including consideration of only diffuse soil-to-groundwater recharge (not from rivers and other surface waters), a primary focus on arid and semi-arid calibration data; and the predictions do not include some information of local interest such as water table elevation changes (Döll and Flörke, 2005).

Future directions in reducing model uncertainty include continued improvement of the ability of the models to simulate real-world physical processes, development of more comprehensive datasets for calibration and continued development of probabilistic approaches that provide better understanding of the likelihood of various model outcomes.

## Linking Global Changes to Local Groundwater Issues

An increasing number of studies have linked global-scale climate models to regional- and local-scale models to allow for local predictions of water-level changes, aquifer discharges or other site-specific information. A typical linkage of models is depicted in Fig. 10.

An advantage of the linked model approach is that it allows for using finely gridded representations of local topography, hydrologic control features, local feedback mechanisms and other features of interest in conjunction with the outcomes from global models. For example, a particular state or regional government may want to use the range of SRES-based climate model outcomes as input to their local groundwater models allowing for comparison of various groundwater management options under future stresses.

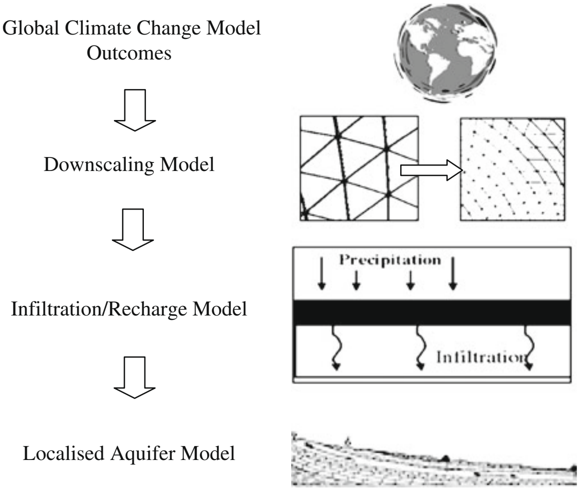


**Fig. 10** Typical model components and linkages used when downscaling from global to local aquifer scales

Global-to-local linked model studies have been increasingly reported in recent years including studies for a karst aquifer in TX, USA (Loáiciga et al., 2000), the Dongjiang Basin, China (Jaing et al., 2007) and the Grand Forks Aquifer area of British Columbia, Canada (Scibek et al., 2007), and include an effort made to predict impacts to the groundwater supply of a specific city – Lansing, MI, USA (Croley and Luukkonen, 2003).

As an example, Scibek et al. (2007) reported modelling results in response to climate change predictions of the unconfined Grand Forks aquifer in British Columbia, Canada. A global climate scenario (IPCC IS92, a greenhouse gas plus aerosol transient simulation) was used in the Canadian Global Coupled Model (CGCM1) to provide for downscaled runoff hydrograph data. These data were in turn used as input to a river flow model using a hydrologic model (BRANCH) coupled with an unconfined floodplain aquifer model (MODFLOW). This linked model approach allowed for predictions to be made in aquifer levels (Fig. 11) in response to the climate scenario. For this study, the projected groundwater level change closely followed projected changes in river discharge with greater than 0.5 m changes near the channel and lesser changes further away from the river. The study indicated that the changes were largely a result of a shift in the timing of the river peak flow to an earlier date in a year, and that the "maximum groundwater levels associated with the peak hydrograph are very similar to present climate because the peak discharge is not predicted to change, only the timing of the peak" (Scibek et al., 2007).

One limitation of this global-to-local linked approach is that water balance and feedback mechanisms are not preserved on a global scale. Results from linked approaches also can be disproportionately sensitive to the downscaling method. One study concluded that the "use of statistical downscaling as a regionalization technique is incompetent if long and reliable observed data series are not available" (Varis et al., 2004). A discussion of various downscaling methods and their uses is provided in Varis et al. (2004). Localised models may also not be calibrated to the range of conditions represented in future climate scenarios. One study found that there was a greater difference in the outcomes among six different hydrologic water balance models of the same watershed when simulating various future climate scenarios compared to their simulation of past historical conditions (Jiang

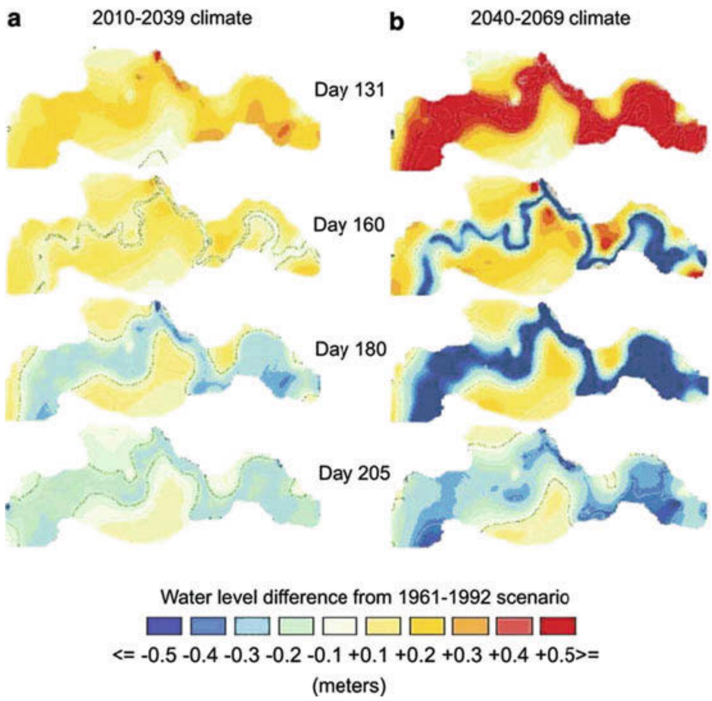


**Fig. 11** Water-level differences (measured as head in layer 2 of the unconfined aquifer) between (**a**) future (2010–2039) and present climate and (**b**) future (2040–2069) and present climate under pumping conditions. Maps by time step in days 131–180. Positive contours are shown at 0.1 m interval. The zero contour is a *dashed line*. Negative contours are not shown. *Darkest blue colours* indicate values <0.5 m (along rivers only). At day 101 (not shown), difference map has values within 0.1 m of zero. (Scibek et al., 2007, figure 15, reproduced with kind permission from Elsevier)

et al., 2007). In 2004, a modelling overview concluded the ability of regional climate models to reproduce the present day climate has substantially improved and that the effects of domain size, resolution, boundary forcing and internal model variability of these models are now better understood (Xu et al., 2005).

## Predictions of Coastal Groundwater Response to Sea-Level Changes

The intrusion of seawater into fresh groundwater in coastal regions has been the subject of numerous studies (Bear et al., 1999), with many recent efforts focused on potential impacts of rising sea levels during climate change. Estimates reported by the IPCC of globally averaged sea-level increases range from 0.19 to 0.58 m through the end of the 21st century as predicted using six SRES scenarios (IPCC, 2007). Sea-level rise is expected to result in the inland migration of the mixing zone between freshwater and saline water (IPCC, 2007).

A study of potential loss of coastal groundwater resources to seawater intrusion suggests higher reductions in the Central American, southern North American, Mediterranean, central African and northern Australian regions (Fig. 12). The study further suggests that coastal areas in Africa show a potential higher loss in fresh groundwater resources than any other region in the world. It used the SRES A2 scenario, HadCM3 GCM data, simplified estimation of groundwater recharge and a steady-state estimation of the saltwater/freshwater interface. The same study recognised that the ability of water resource managers to respond depends on not only "the level of climate change, but also population growth and changes in demands, technology and economic, social, and legislative conditions highlighting the importance of an Integrated Coastal Management practices in coastal areas at both national and regional levels" (Ranjan et al., 2009).

One of the keys to any modelling approach for estimating seawater intrusion potential is the treatment of the saline/freshwater interface. Representation of the interface in models typically invokes assumptions of either a flux-controlled system where the flow across the interface is constrained and groundwater levels vary or a head-controlled system having the opposite assumptions of groundwater levels being constrained and interface flow allowed to vary. A report on a generalised modelling study highlighted the importance of the constraints placed on the interface

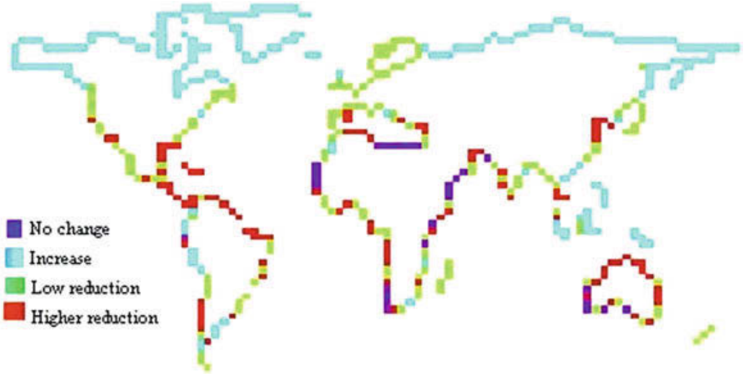


**Fig. 12** Modelled change in fresh coastal groundwater resources over the next century (Ranjan et al., 2009, figure 5, reproduced with kind permission from Elsevier)

when performing seawater intrusion modelling. In the case of the head-controlled condition, the seawater intruded up to several kilometres inland for an assumed 1.5 m rise in sea levels. In contrast, a relatively short distance of not more than 50 m resulted from the assumption of a flux-controlled condition. Both cases assumed steady-state conditions and the same typical values of recharge, hydraulic conductivity and aquifer depth (Werner and Simmons, 2009).

## Island Groundwater Impacts

Low-lying islands have similar seawater intrusion potentials as other low coastal areas, but face heightened challenges in that island aquifers are typically relatively limited in extent and often reside in volcanic or coral-derived material conducive to seawater intrusion as compared to most continental aquifers.

A case study on a western Pacific atoll tested potential impacts of extended drought, including El Niño cycle effects, on the atoll's freshwater lens. Results suggest that the thickness of the freshwater lens depends on recharge rate, island width, depth to the Thurber Discontinuity (see Fig. 13), hydraulic conductivity of the Holocene sediments and the presence or absence of a reef-flat plate. The lens thickness is greatly diminished during a drought associated with an El Niño event. This depletion is most drastic for small atoll islets, windward atoll islets and regions with relatively low rainfall rates. Recovery from a 6-month drought was estimated to require about 1.5 years for the atoll considered (Bailey et al., 2009).

The authors of the above study generalise that current knowledge of atoll aquifer geology and climatic phenomena, coupled with the power of current numerical modelling technology, allows modellers to predict aquifer performance with sufficient confidence to provide water resource managers with useful estimates of how groundwater resources on a given island may be affected by predictable climatic events (Bailey et al., 2009).

## Groundwater Quality Implications of Carbon Sequestration

Carbon dioxide sequestration has emerged as an important alternative for reducing global greenhouse emissions. If this method is to be used to combat rising $CO_2$ levels or even reduce them, huge volumes of $CO_2$ must be sequestered to reduce global carbon levels to below pre-industrial conditions (Benson and Cole, 2008). Large sedimentary basins have been identified as the most suitable mediums for $CO_2$ sequestration. The major problem concerning the use of these systems to sequester $CO_2$ is that they generally also contain large potable groundwater resources. To protect these groundwater sources, $CO_2$ sequestration needs to be limited to deep (∼greater than 800 m) and preferably saline aquifers (Benson and Cole, 2008) that are disconnected from the land surface or from any other water resource.

Isolation of the $CO_2$ is complicated due to the changes brought on by introducing the $CO_2$ itself. When $CO_2$ is injected into a deep geological formation, it displaces the pore fluid or groundwater contained with the pore spaces. Injecting $CO_2$ promotes geochemical reactions that can alter the thermodynamic balance between the groundwater and the aquifer sediments. Once injected some $CO_2$ dissolves in the existing groundwater, decreasing the pH of the

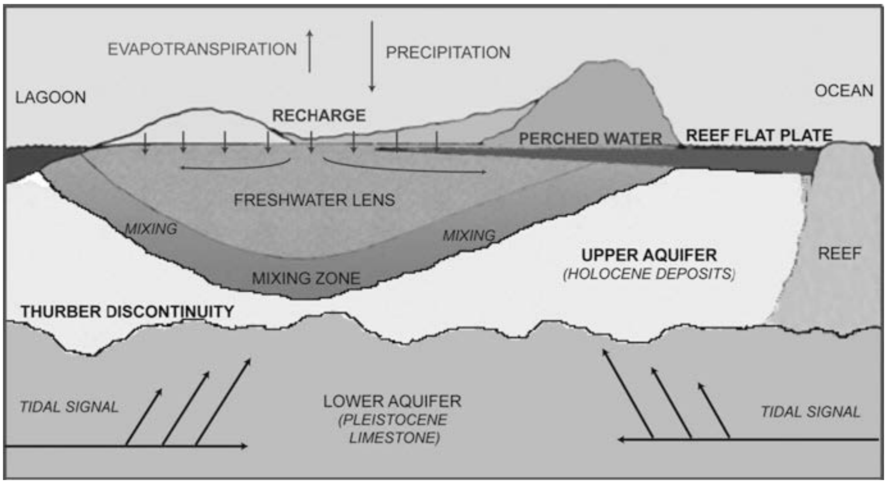


**Fig. 13** Conceptual model of the hydrogeology of an atoll island (after Ayers and Vacher 1986, redrawn from *Ground Water* with permission of the National Ground Water Association. Copyright 1986)

water from around neutral to acidic (pH < 4). Acidic waters have a greater potential to dissolve minerals in the geological unit that they come in contact with. These chemical reactions can then alter the pore volume and connectivity of the aquifer. Most importantly for the groundwater quality, these chemical reactions can lead to the mobilisation of inorganic and organic contaminants into potable groundwater (Kharaka et al., 2006a; Kharaka et al., 2006b). To monitor the migration and fate of sequestered $CO_2$, a comprehensive geophysical and geochemical monitoring programme is needed (Benson and Cole, 2008). The economic and environmental costs involved in sequestering $CO_2$ in deep geological formation are enormous and one must consider whether $CO_2$ emission reduction is a far simpler approach than sequestering the excess $CO_2$ produced by anthropogenic influences.

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# Linking Runoff to Groundwater in Permafrost Terrain

Ming-Ko Woo

**Abstract**

Frozen materials with abundant ground ice are impermeable to groundwater movement and storage. Suprapermafrost groundwater in the active layer (seasonally frozen and thawed zone) is limited in quantity but important for runoff generation. Subsurface flow of this shallow groundwater normally follows soil pipes or through the soil matrix, the latter being strongly influenced by the hydraulic conductivity of the soil material, notably peat which commonly forms the top horizon. Exfiltration of this water gives rise to various expressions of surface runoff that include saturation overland flow on slopes, rills and gullies and drainage along ice-wedge cracks, wetlands or ponds. In discontinuous permafrost areas, deep groundwater from subpermafrost zone can also feed to wetlands, lake beds and streambeds or emerge as springs that may be thermal or saline in nature. Deep groundwater is especially important in karst areas where solution conduits in carbonate rocks provide subterranean flow passages. Suprapermafrost groundwater is not a reliable source for streamflow but subpermafrost groundwater discharge offers a stable base flow for rivers in discontinuous permafrost terrain.

**Keywords**

Active layer • Ground ice • Groundwater flow • Icing • Peat • Permafrost • Runoff • Streamflow • Subsurface flow • Wetlands

## Introduction

Permafrost is earth materials with temperature of 0°C or below for at least two consecutive summers. In permafrost areas, groundwater can occur above, within or beneath the perennially frozen ground, and they are termed surpa-, intra- and subpermafrost groundwater (Tolstikhin and Tolstikhin, 1976; Williams and Waller, 1966). Note that permafrost is defined on the basis of temperature and not on freeze-thaw state of water in the ground. A zone in the permafrost that remains unfrozen is called a talik. Cryopeg is unfrozen zone that is perennially below 0°C but freezing is prevented by freezing-point depression that maintains the soil water in a liquid state. Taliks and cryopegs

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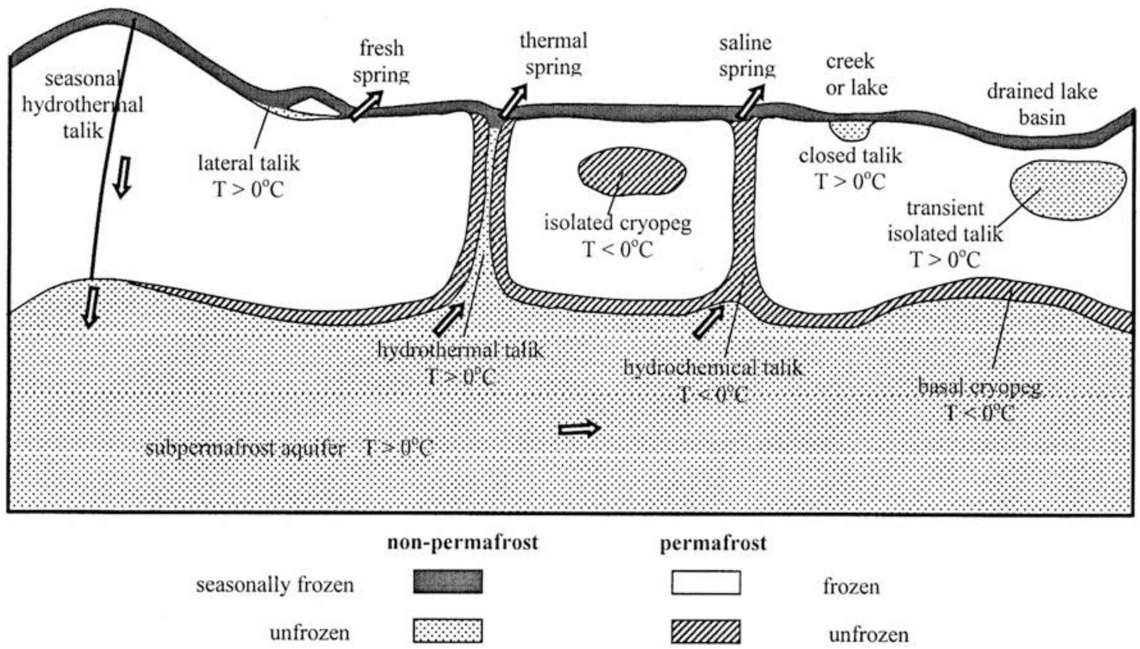


**Fig. 1** Groundwater system in permafrost terrain (modified after van Everdingen, 1987)

provide opportunities for storage and movement of intrapermafrost groundwater. Above the permafrost is the active layer which freezes in winter but thaws in summer, and this is the layer where suprapermafrost groundwater occurs. Figure 1, modified after van Everdingen (1987), is a schematic representation of these features in permafrost terrain.

Surface runoff is generated when groundwater emerges above ground. The flow can spread as sheets of water overland or can follow channels along rills and streams or seep through wetlands, river and lake beds. This chapter presents a brief survey of the relationship between groundwater and runoff generation in permafrost areas.

## Active Layer and Suprapermafrost Groundwater

The active layer has several major attributes. (1) Mean thickness of this layer generally attains equilibrium with the climate but in detail, there are year-to-year fluctuations that can vary by centimetres to tens of centimetres, depending on variations in annual air temperature and in snow cover conditions, with snow being a good insulator against ground chill. Below the active layer is a zone that thaws only during exceptionally warm years. It is the transition layer that usually is enriched with ground ice (Shur et al., 2005). Active layer thickness decreases towards the poles but under climate warming, its thickness is expected to increases. (2) Water in this layer is stored in solid form (ground ice) in the cold season. As frozen soil is often impermeable, the liquid water storage capacity of the active layer changes during the thaw season depending on how deep the ground has thawed. When thawed, ground ice held in storage is released and provides water even during periods without inputs from the surface or from lateral recharge. (3) This layer is the zone where meteoric water enters the ground. Recharge from snow meltwater is governed by the opportunity to infiltrate the frozen soil which may range from unlimited infiltration in gravels to restricted infiltration in icy silt (Gray et al., 1985). Rainwater, often not as large in quantity as snowmelt in the permafrost environment, can enter the active layer more readily as the ground is usually thawed in times of rain. (4) Groundwater transmission through the active layer is dictated not only by the stratigraphy and intrinsic hydraulic conductivity of the ground materials but also by the ground temperature because hydraulic conductivity drops by orders of magnitude when soil temperature falls below the freezing point (Burt and Williams, 1976). (5) Groundwater is discharged through the active layer, including the water of supra-, intra- and subpermafrost origins. Exceptions are the recharge and discharge of subpermafrost groundwater through taliks below deep water bodies.

## Runoff from Shallow Groundwater

### Seasonality of Runoff

Unless the soil is highly porous and with little ground ice, the presence of frozen soil at shallow depths prevents deep percolation and the closer the frost table is to the surface, the more readily the suprapermafrost water rises in response to water input. During the snowmelt season, the frozen ground is at or very close to the topographic surface. The bulk of meltwater input is shed as surface flow. As ground thaw progresses, there is an increase in the capacity of the active layer to retain the recharged water as well as to generate subsurface flow.

Most of the year's runoff is produced directly from snowmelt and not from groundwater. Figure 2 is an example of the surface and subsurface flows that occurred at a slope in continuous permafrost area (Resolute, Cornwallis Island, Canada, 74°43′N, 94°45′W). Surface flow was produced when thaw was shallow, the ground was saturated and the water table was above ground. Subsurface flow was several times less than surface runoff. After snowmelt, groundwater was consumed largely for evaporation, and this reduced the storage in the active layer. To raise summer flow, the depleted storage had to be replenished before runoff could resume.

For slopes underlain by permafrost in a discontinuous permafrost environment, the suprapermafrost groundwater flow may contribute more to total runoff than in continuous permafrost areas. An example is from a north-facing slope with peat overlying mineral soil (Wolf Creek near Whitehorse, Yukon, Canada, 61°32′N, 135°31′W). In the snowmelt period of 12–27 May 1997, surface rills yielded 53% of total flow, soil pipes accounted for 21% while matrix flow in the organic layer yielded 26% (Carey and Woo, 2000). After snowmelt, slope runoff decreased abruptly but rose gradually in June (Fig. 3) as groundwater arrived from upslope (Carey and Woo, 2001a). Then, as the water table dropped into the mineral substrate, runoff declined even though the active layer thawed to a greater depth that reached 1.5 m in September. For the entire field season, the snowmelt period yielded 155 mm of runoff which was combined surface and subsurface flows and 97 mm of summer flow which was entirely of subsurface origin.

### Subsurface Flow

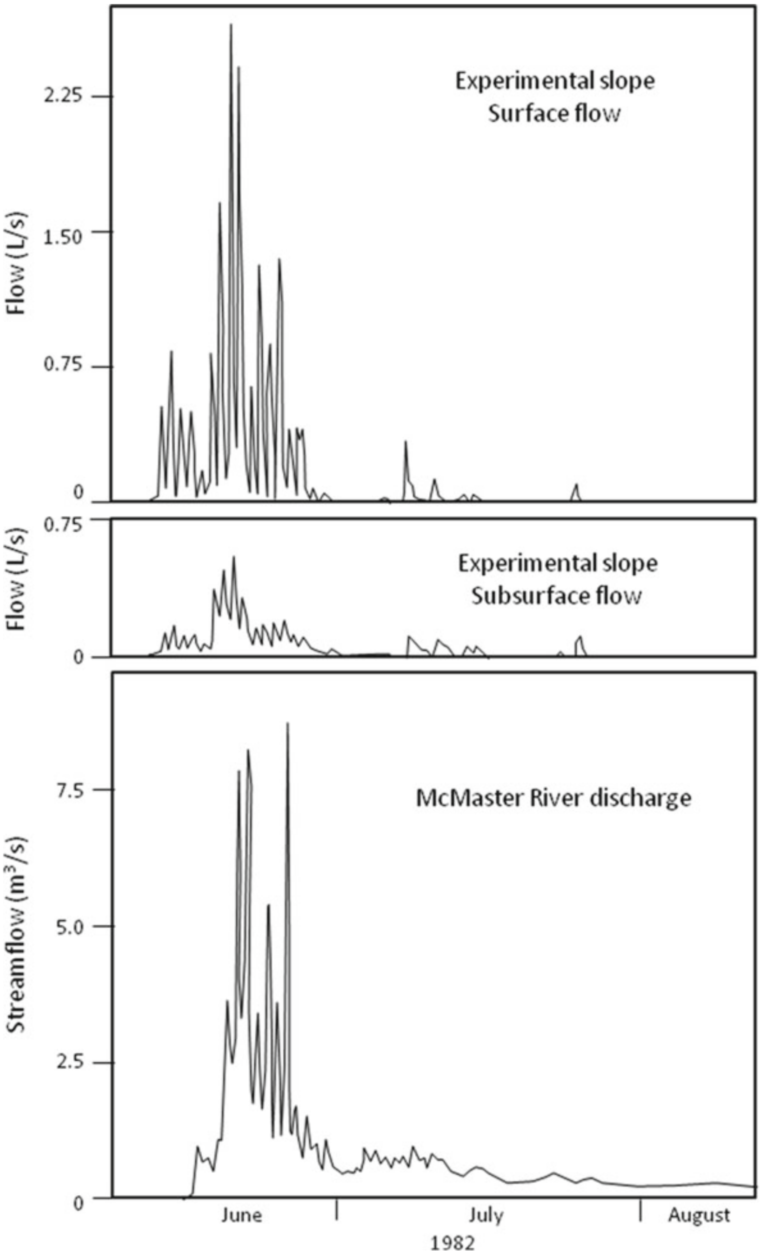
The position of the water table relative to the stratigraphic horizons and to the frost table is a significant determinant of subsurface flow generation. Figure 4 is a schematic presentation of suprapermafrost groundwater flow zones as delineated by three surfaces: the topographic surface, water table and frost table. Groundwater flow through the soil matrix is controlled by the hydraulic conductivity of the medium. A large amount of ground ice that seals the soil pores renders the soil practically impermeable so that suprapermafrost groundwater flow in almost all soils (other than boulders and dry gravels and sand) is restricted to the zone above the frost table.

The frost table is often uneven and its configuration changes during the thaw season. A subsurface ridge of frozen ground can become a temporary barrier to groundwater drainage from upslope. Wright et al. (2009) found impoundment of subsurface water behind such frozen sills. Suprapermafrost drainage resumes only when the water table rises above the lips of the sills or when continued ground thaw removes or lowers these sills. In some cases, the frost table topography may not correspond with the surface relief, and groundwater can be diverted across the topographic drainage divide (Fig. 4). Such a situation has been demonstrated by injecting dye into the ground to find that the dye emerged from a neighbouring catchment (Woo and Steer, 1983).

Bedrock sills perform a similar function in halting subsurface flow from upslope until the water table rises above the sills. In a discontinuous permafrost area near Yellowknife where thin soils cover the Canadian Shield, Spence and Woo (2003) noted that a bedrock sill underneath a soil-filled valley stopped groundwater flow during a dry summer when the water table was lower than the elevation at the lip of the sill.

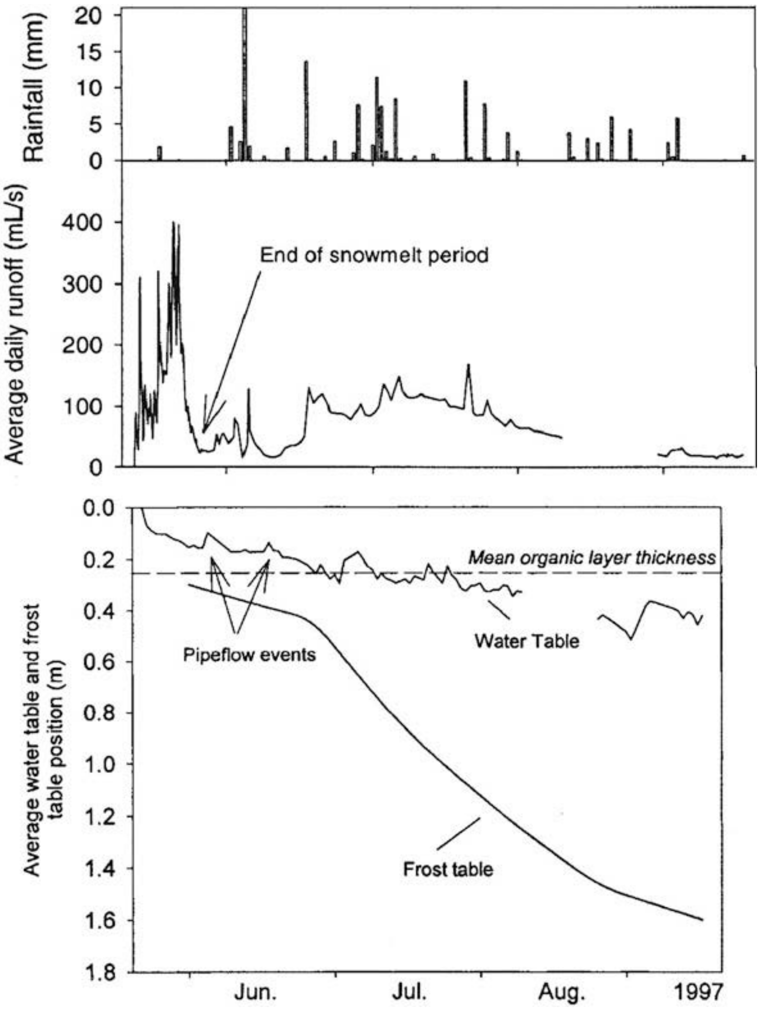
In organic terrain, a combination of intrinsic hydraulic conductivities of peat and mineral soils and

**Fig. 2** Runoff from an Arctic slope in a continuous permafrost area: (*top*) surface flow and (*middle*) subsurface flow. Also shown (*bottom*) is the hydrograph of a typical nival regime river, McMaster River, Resolute, Nunavut, Canada



frost gives rise to preferred groundwater flow paths. Many peat layers have developed a profile that comprises a hydrologically dynamic horizon called the acrotelm on top of a humified and compacted layer called the catotelm. The hydraulic conductivity of the peat layer can vary from $10^2$ m/day near the surface to 1 m/day at about 0.5 m depth (Quinton et al., 2008). Arctic areas with earth hummocks have organic materials filling the interconnected troughs (which measures tens of centimetres deep and tens of centimetres to over a metre across) between individual hummocks composed of mineral soil. High hydraulic conductivity of the organic materials together with the depressed micro-topography concentrates both groundwater and surface flows along the troughs (Quinton and Marsh, 1999). Where a subarctic slope has an extensive organic cover on mineral soils, percolation is retarded at the catotelm or at the organic–mineral interface as the hydraulic conductivity drops abruptly, especially if the catotelm or the mineral substrate is frozen.

**Fig. 3** Water table, frost table and runoff from a subarctic slope with permafrost, Wolf Creek, Yukon, Canada



When the water table is within the acrotelm, quick flow is delivered though matrix flow and along soil pipes formed in the organic layer. As frost table descends and as evaporation draws down the suprapermafrost groundwater, the water table drops below the acrotelm. Then, slope runoff is maintained only by slow flow which is orders of magnitude lower than the near-surface quick flow. Such a mechanism of runoff is called a two-layer flow system (Carey and Woo, 2001b).

As many parts of the Arctic and Subarctic have an extensive peat cover, the two-layer flow system has significant effects on water delivery from hillslopes to the streams. Quinton and Marsh (1999) described a small, 99.5 ha, Arctic Basin with thick peat (0.4–0.7 m) along the near-stream area that extends 10–40 m upslope, and thin peat (<0.3 m) that continues into the upland area. For practical considerations, the acrotelm when not frozen provides the aquifer for quick flow. Under wet conditions, the saturated zone extends as a continuum throughout much of the basin to provide water to the stream. In the dry summer, only the near-stream zone is the source area and slow flow alone is produced when the water table falls below the acrotelm. With input events such as rainstorms, lateral expansion of the source area to the upland zone is delayed because the depleted storage in the near-stream zone has to be recovered. However, quick flow can still occur if the water table rises to the highly conductive acrotelm in the near-stream area. Thus, the extent of the saturated peat layer in a basin, the elevation of the water table in the peat and the width of the near-stream zone influence the subsurface hydrological linkage among the upland, the near-stream area and the stream channel.

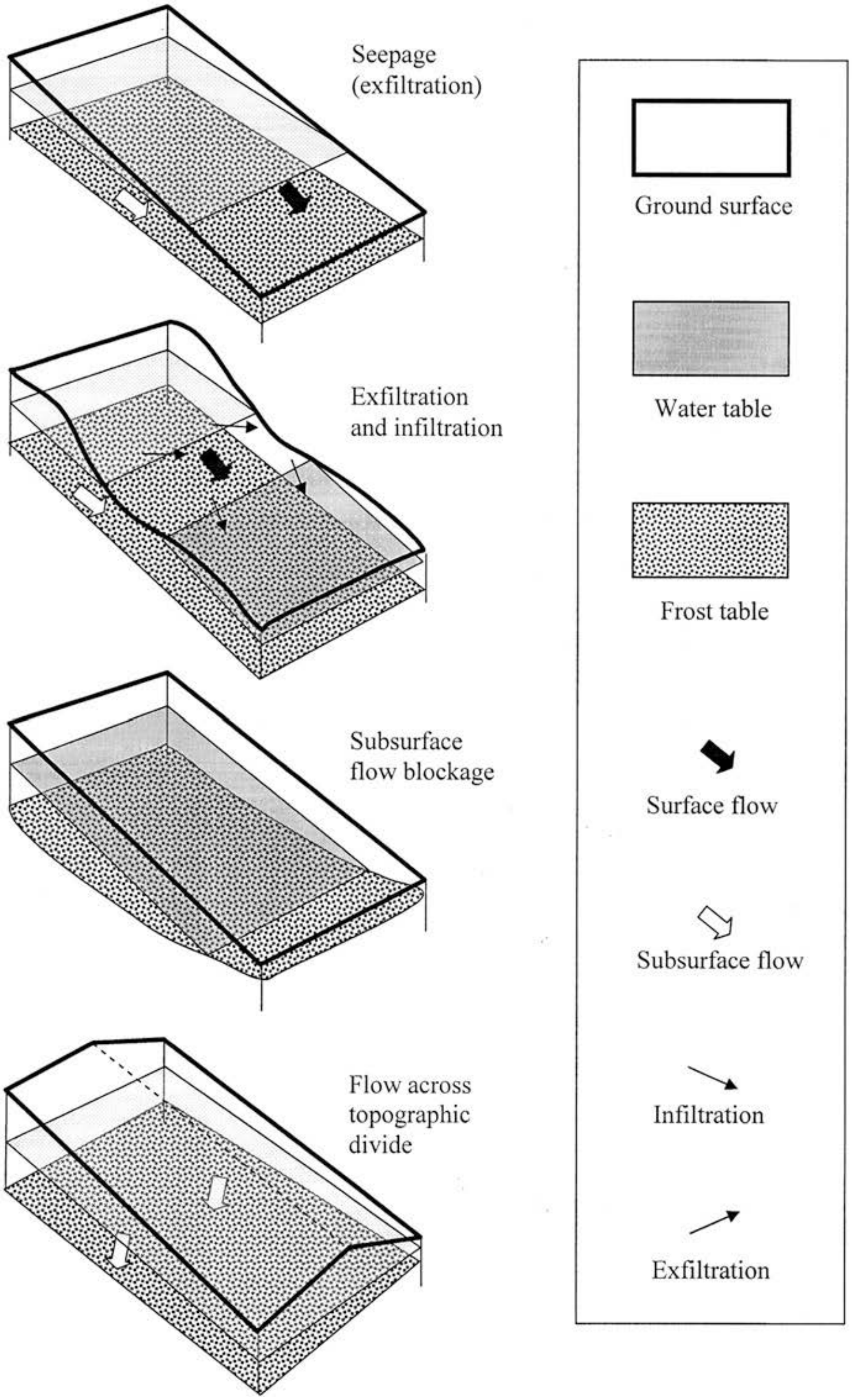


**Fig. 4** Schematic diagrams showing runoff generation from a permafrost slope. Relative positions of three surfaces (ground surface, water table and frost table) determine the occurrence and direction of surface and subsurface flows

In terrain where moderately steep slopes meet a flat-bottom valley, there may not always be a saturated belt at the footslope; therefore instead of a gradual expansion and contraction of the source area, hillslope water supply to the valley can terminate abruptly in the dry period. A valley fen in Hot Weather Creek Basin, Ellesmere Island, Canada, becomes hydrological disconnected with its adjacent slopes during the dry season after the snowmelt-sustained suprapermafrost groundwater has drained from the slopes (Glenn and Woo, 1997).

## Surface Runoff: Non-channelled Seepage

Similar to subsurface flow production, the relative positions of three surfaces are important in terms of surface runoff generation (Fig. 4). A shallow *frost table* limits the saturated zone and helps to lift the *water table* close to the *ground surface*. Water seeps from a slope when the water table is high enough to intersect the ground surface. Concave slope segments are preferred seepage sites. The upper part of the concavity has a steeper gradient to yield faster inflow than can be dissipated by the outflow at the lower slope. This raises the water table above ground at the break of slope to generate seepage. The reverse occurs at a convexity. A slope that consists of a sequence of convexities and concavities exhibits alternating groundwater influence and effluence.

Recurrent seepage gives rise to a saturated zone on a slope where saturation overland flow is produced. In topographic depressions with impeded drainage, a pond can be maintained. It is noted that the maintenance of a permanent pond by shallow groundwater (which has considerably lower yield than groundwater from a subpermafrost source) requires a drainage collection area that is orders of magnitude larger than the surface area of the pond (Marsh and Woo, 1977). When conditions are favourable for the growth of hydrophytic vegetation and the formation of peat, a patchy wetland can be created. The wetland is hydrologically sustained by groundwater seepage, surface runoff that enters it laterally and snowmelt and rainwater that fall directly on the wetland (Woo et al., 2006).

Extensive wetlands comprise many patches with different hydrological, chemical and ecological characteristics. Arctic wetlands may have tundra ponds, wet meadows, fens and mesic ground interconnected by surface and subsurface flows during parts or all of the thaw season (Woo and Young, 2006). Hydrologic connectivity is most extensive during the snowmelt period when shallow ground thaw and ample meltwater supply facilitate surface runoff. As the frost table deepens and evaporation loss increases, the water table drops and surface flow connections among many wetland patches are severed (Bowling et al., 2003). Even subsurface flow linkages are reduced or cut off as the water table declines further and some tundra ponds and mesic ground may become isolated from their upslope water sources (Woo et al., 2008).

In subarctic wetlands, Quinton et al. (2003) identified peat plateaus of saturated permafrost that rise above isolated bog patches and fens and channel fens. Each of these organic terrain types has a different hydrological function. Groundwater from the peat plateaus is either shed to their adjacent bogs that serve mainly as a storage or feeds laterally to the channel fens that transfer water towards the basin outlet.

## Surface Runoff: Channelled Flow

In the barren, polar desert landscape, ephemeral rills are common on slopes, especially below topographic concavities which trap more snow than their surrounding. Melt runoff from late-lying snowbanks (Young and Lewkowicz, 1988) produces surface and shallow groundwater flows that feed the rills. Enlargement of these rills can form stripes (geomorphological term). In the Low Arctic with tundra vegetation cover, slope runoff may concentrate along water tracks (McNamara et al., 1999), marked by a change of vegetation, that convey water mainly in the snowmelt period. On slopes where soil pipes have formed, a collapse of their roof transforms the pipes into rills and the submergence or emergence of flow follows a pipe–rill network (Carey and Woo, 2000).

Groundwater can initiate gullies without going through the stage of rill formation. Figure 5 shows a gully developed in gravels in Resolute, Canada. In 1994, flow began on June 15 and showed prominent diurnal fluctuations until July 1, suggesting strong influence of snowmelt. After that, groundwater was the main if not the exclusive water source. Flow ceased in mid-July, as the water table could not be raised sufficiently by a rain event but when steady drizzle

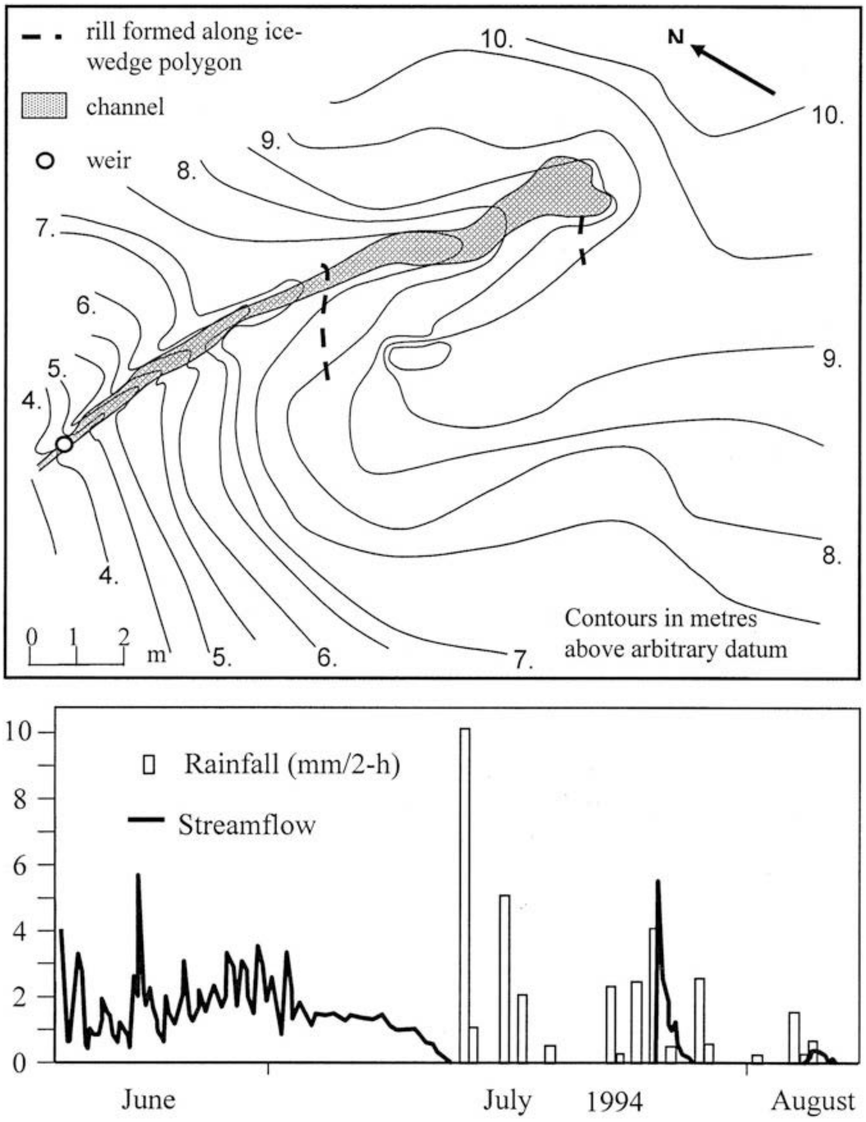


**Fig. 5** Streamflow in a gully fed by suprapermafrost groundwater in gravels, Resolute, Canada

during July 22–24 prepared the groundwater reservoir for a 16 mm event on July 25, gully flow was quickly revived for a few days (Woo and Xia, 1995).

Continuous permafrost terrain is cut by networks of ice-wedge polygons. The cracks of the polygons, sometimes reaching several metres in width, offer natural troughs for water storage and conduits of flow. Unless blocked by raised frozen rims along the cracks, suprapermafrost groundwater can seep into these troughs while melting and erosion of the wedge ice on the trough floors yields an additional supply of water (Fortier et al., 2007).

## Discharge of Deep Groundwater

Deep groundwater from subpermafrost zone may be connected to the ground surface through intrapermafrost taliks. Being capped by impervious permafrost, this water is under artesian pressure.

Discharge may occur as springs (Fig. 1). Thermal springs have temperature above 10°C and the heat of the water maintains an open passage through the permafrost layer. Mineral springs are also perennial as their high concentration of dissolved solid (exceeding 1 g/L) depresses the freezing point. Most springs emerge from discontinuous permafrost areas. On rare occasions, geothermal and saline springs have been reported in the High Arctic where permafrost is continuous and thick (Pollard, 2005). Faults facilitate the flow of intrapermafrost groundwater. Williams and van Everdingen (1973) noted the issuance of large springs in the Brooks Range (Alaska) and British Mountains (Yukon) from fault zones, producing enormous sheet-like mass of layered ice called icing (known as Aufeis in German and naled in Russian) downstream. A special situation is where human activities create artificial flow routes. Haldorsen et al. (1996) gave an example from Ny-Ålesund in Svalbard where subpermafrost groundwater is discharged along outflow channels in an old coal mine.

Deep groundwater exchanges water with many lakes in the discontinuous permafrost areas. The existence of taliks below lakes offers linkage with the subpermafrost aquifers (Kane and Slaughter, 1973). Myriads of thermokarst lakes and ponds in discontinuous permafrost regions may or may not be linked to the subpermafrost reservoir. Many of the ponds currently fed only by suprapermafrost groundwater may be seriously affected by climate warming. There is evidence that deepening of thaw in the past decades has punctured the thin permafrost that seals the bottom of some water bodies. The resulting drainage has led to shrinkage or disappearance of some lakes and ponds in Alaska and Siberia (Smith et al., 2008; Yoshikawa and Hinzman, 2003).

Carbonate terrain has numerous sinkholes and subterranean openings of tunnels and caves created by solution of limestone and dolomite. Large depressions including poljes may be flooded to form temporary lakes when surface water input exceeds the capacity of underground storage and drainage. Brook (1983) gave an example in Nahanni, Northwest Territories, Canada, where a polje was flooded when an extreme summer rainstorm yielded 224 mm of rain in 1972 that could not be rapidly removed through the karst labyrinths. These temporarily lakes would drain subsequently and vegetation grows on the floors until another flood event.

## Winter Discharge of Groundwater

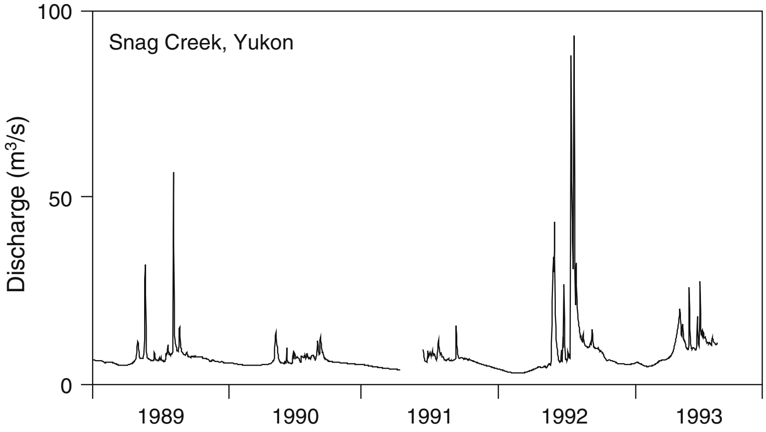
Under extreme cold conditions of the winter experienced in permafrost regions, ice is formed of the water that flows within and above ground. The most common occurrences are the freezing of soil water in situ to produce pore ice (ice between soil particles) and reticulated ice (ice in soil cracks) and the creation of segregated ice that forms lenses as soil water migrates to the freezing front and freezes (National Research Council of Canada, 1988). Where groundwater flow is impeded, the water collected freezes as an ice core and lifts the seasonally frozen ground to produce a frost blister (Fig. 1). Where water ruptures through the frozen cap, it is quickly frozen to form icing. Icing can be distinguished into ground, spring and river icing according to location of occurrence (Carey, 1973). Icing growth terminates when the suprapermafrost groundwater supply is exhausted though connections to intra- and subpermafrost groundwater sources will extend the duration of icing formation.

The discharge of perennial spring in discontinuous permafrost region can maintain open water sections along rivers during winter. River icing is also common and its growth is closely connected with groundwater flow conditions along the streambed and streambanks (Kane, 1981). In some rivers, most or all of the winter base flow may freeze as icing. The Babbage and Firth rivers in Yukon, Canada, record no winter flow but they produce thick icings. Spring-fed discharge rates of 1.4 and 0.9 $m^3s^{-1}$ had been measured in the upper Babbage River and upper Firth River, respectively (van Everdingen, 1987). For large rivers, icing thickness can exceed 10 m and its ablation in the summer can be an effective water source for streamflow (Sokolov, 1991). In this regard, river icing may be considered as surface storage of subsurface water.

## Groundwater and Streamflow

In the continuous permafrost region, suprapermafrost groundwater supply is limited when the ground is thawed and it is unavailable in the winter. The bulk of river discharge is provided by surface runoff, notably during the periods of snowmelt and intense rain, and flow ceases throughout the winter. This is the nival regime of flow (Church, 1974), as exemplified by

**Fig. 6** Discharge of a stream in discontinuous permafrost area with stable base flow supported by subpermafrost groundwater, Snag Creek, Yukon. Spikes in the hydrograph are due to snowmelt and rainfall inputs



McMaster River (area 33 km$^2$) in Resolute, Canada (Fig. 2 bottom).

In discontinuous permafrost areas, subpermafrost groundwater provides much of the base flow which can maintain low flow in rivers throughout the winter. The Snag Creek in Yukon Territory, Canada, offers an example (van Everdingen, 1988) of a river with year-round discharge (Fig. 6). The most notable contribution of groundwater to streamflow occurs in carbonate terrain. Clarke et al. (2001) found that only during spring melt is suprapermafrost water a major component of streamflow, and most of the base flow comes from groundwater source. Seepage of perennial springs supports the flow throughout the year. The characteristic seasonal flow pattern is the spring-fed regime (Woo, 1986) in which the flow is relatively stable throughout the winter and the dry periods of the year, with added runoff from snowmelt and heavy rain superimposed upon the steady flow (Fig. 6).

## Conclusions

Although snowmelt and rainfall are responsible for generating much of the runoff in permafrost terrain, it is the groundwater that usually maintains low flow and evaporation in the summer and for discontinuous permafrost areas, winter flow and icing formation.

Suprapermafrost groundwater in the active layer is the more dynamic among the several types of groundwater in permafrost. It takes in snowmelt and rainwater and is discharged as runoff or as recharge to the deeper groundwater reservoir in discontinuous permafrost areas. Subpermafrost groundwater may be connected to the surface through intrapermafrost conduits. Subsurface water movement occurs in soil pipes or matrix flow, the latter being strongly influenced by intrinsic hydraulic conductivity of the soil and the amount of ground ice present. Groundwater exfiltration is manifested as seepage that supports lakes, ponds and wetlands or takes on surface expressions as springs, saturated overland flow, rills, water tracks and gullies.

Permafrost plays an important role in affecting streamflow. A shallow frost table ensures rapid response of runoff to meltwater and rainwater inputs so that the hydrograph rises and peaks quickly and the runoff ratio is often large. Where subpermafrost water is a major contributor, especially in carbonate terrain, base flow is a major component of stream discharge and streamflow is much more stable than that of rivers with suprapermafrost groundwater as the sole subsurface source. In winter, groundwater discharge produces icing which does not melt until the next thaw season. In this case, permafrost groundwater yields not only immediate runoff but also the flow of subsequent years.

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# Geography of the World's Groundwater: A Hierarchical Approach to Scale-Dependent Zoning

Jac van der Gun, Slavek Vasak, and Josef Reckman

**Abstract**

The description and analysis of local, regional or global groundwater conditions are of practical use only if the groundwater information is properly linked to well-defined geographic locations or zones. Most hydrogeological maps do so by presenting values or patterns of hydrogeological variables superimposed on a simplified topographic map. For various purposes, however, it is helpful to relate the groundwater information to predefined spatial units or zones with hydrogeologically meaningful boundaries. Such zones can be defined at different scale levels, according to the geographic dimensions of the case considered and the spatial resolution required. In this chapter, a hierarchical approach to scale-dependent groundwater zoning is presented. It includes three levels: (1) 'aquifers' or 'aquifer systems' at the local level; (2) 'groundwater provinces' at the intermediate level; and (3) 'global groundwater regions' at the macro-level. Each of the delineated 36 global groundwater regions is subdivided into a number of the 217 proposed groundwater provinces. Each of the latter, in turn, includes one, several or many of the aquifer systems present on Earth. The proposed zoning system has potential to contribute to organising, deepening and disseminating knowledge on the World's groundwater.

**Keywords**

Groundwater • Geography • Aquifers • Zoning • Aquifer systems • Groundwater provinces • Global groundwater regions

## Introduction

The World's groundwater is characterised by an almost endless geographical variation in setting, state, potential, processes and interactions. Consequently, huge efforts have been and still are being spent worldwide on the reconnaissance, exploration, assessment and monitoring of groundwater. The objective of the vast majority of these activities is collecting site- and area-specific information as an indispensable

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basis for the planning of groundwater development and/or groundwater resources management. Point observations can be filed and mapped as functions of three spatial coordinates (X, Y and Z) and time. However, for analysing and understanding local groundwater properties, phenomena and behaviour properly, point observations need to be interrelated and integrated into a larger spatial unit that forms the cornerstone of a conceptual model. Even most hydrogeological maps fail to do so, as they tend to display spatial patterns of hydrogeological variables or classes rather than to delineate discrete and coherent spatial groundwater units (see Fig. 1).

After Dominique Arago introduced in 1834 the concept ‘aquifer’ (or ‘système aquifère’, as he called it) in French hydrogeology (Margat, 1996), the aquifer has become the most commonly used type of spatial unit in hydrogeology. It is defined as ‘a saturated permeable geological unit that can transmit significant quantities of water under ordinary hydraulic gradients’ (Freeze and Cherry, 1979) or ‘a saturated bed, formation or group of formations which yields water in sufficient quantity to be of consequence

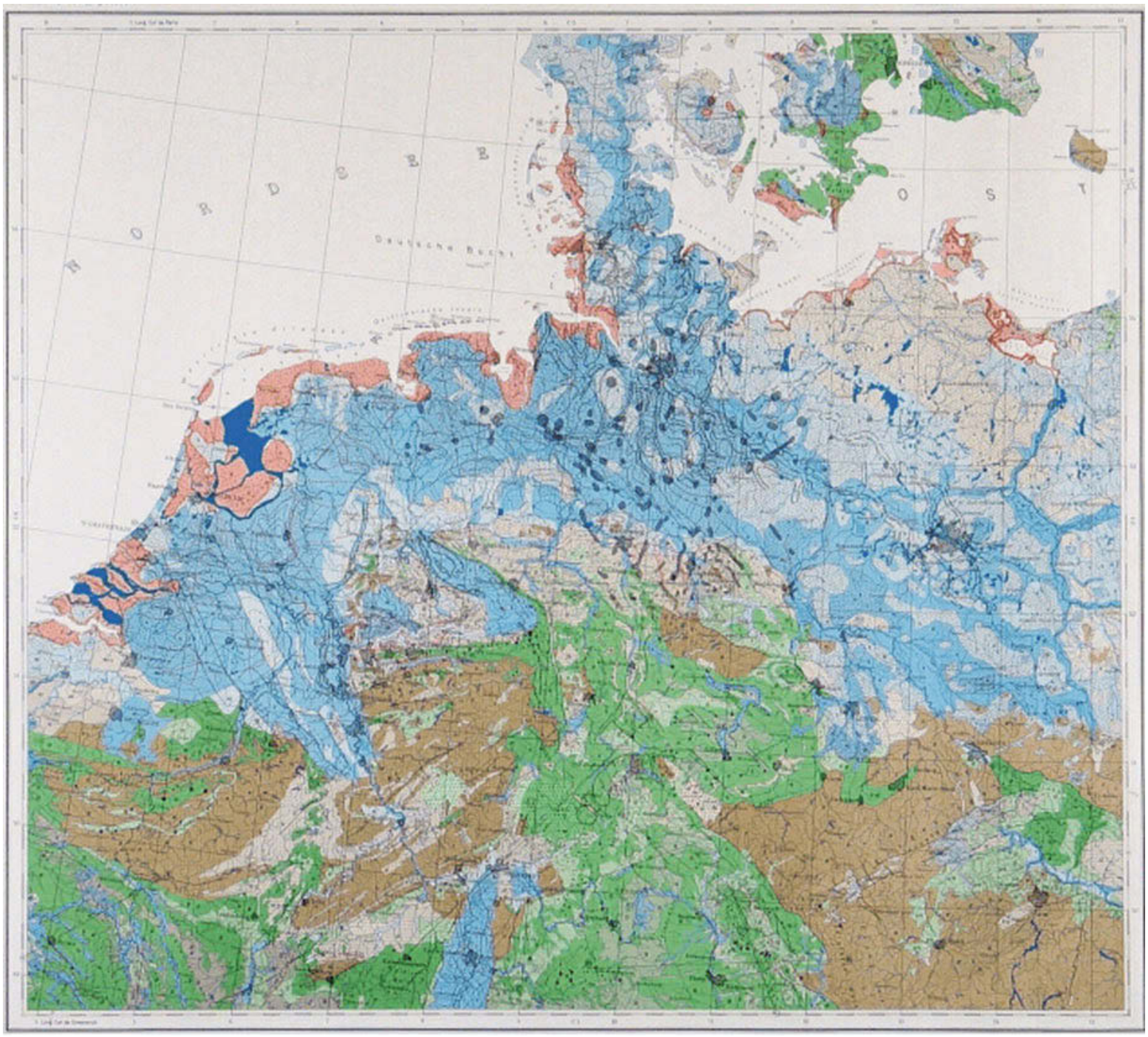


**Fig. 1** International Hydrogeological Map of Europe, sheet C4 (Berlin), as an example of a conventional hydrogeological map using IAH-UNESCO legend (original scale 1: 1.5 million; reproduced with permission from Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany)

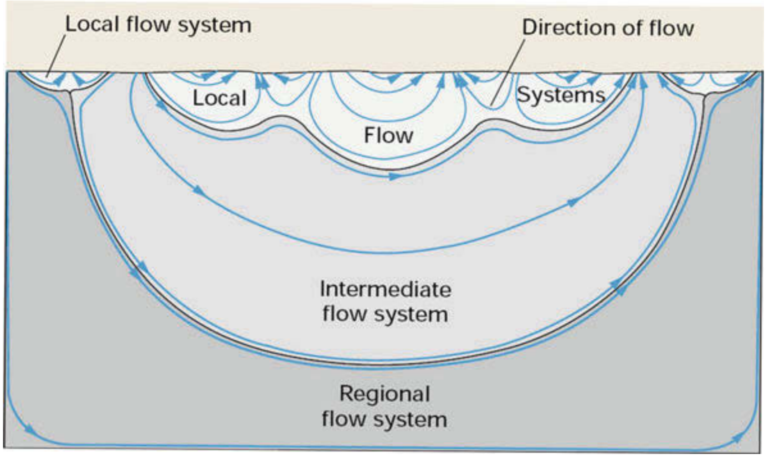


**Fig. 2** Tóth's nested groundwater flow systems (redrawn by Winter et al. (1998) after Tóth, 1963)

as a source of supply' (Walton, 1970) or 'a subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater' (European Communities, 2003). Aquifers are assumed to be hydraulically continuous and to border horizontally and vertically on non-aquiferous bodies, such as aquitards, aquicludes or the unsaturated zone. In other words, they can be interpreted as single groundwater reservoirs. The aquifer concept is not only compatible with the 'system concept' in systems theory; it is also very expressive in the communication on groundwater, both among specialists and with the general public. Especially the tradition of giving a name to aquifers does strengthen their identity and helps memorising and interrelating available aquifer-related information.

Depending on the envisaged application, there may be reasons sometimes to prefer spatial units other than aquifers. Such reasons may be related to the angle of view or to the relevant spatial scale. A first illustration forms the 'flow systems approach' developed and promoted by József Tóth (1963). It focuses on the delineation of so-called groundwater flow systems – in principle having dynamically changing boundaries – often in a nested configuration from local to regional systems (see Fig. 2). Many hydrogeologists consider these flow systems to be more convenient spatial units than aquifers for studying spatial variations in groundwater quality. Another example is the concept of 'groundwater body', as used under the Water Framework Directive of European Union (European Communities, 2003). EU member states have to identify and delineate 'bodies of groundwater' as elementary spatial units for monitoring and managing the state of groundwater quality. These bodies tend to be much smaller than aquifers, given the criterion that they should be reasonably uniform.

Considerations of scale play an important role, too. A hydrologically motivated subdivision of aquifers into recharge, transmission and discharge zones leads to the delineation of spatial units smaller than aquifers. The same is true if the evolution of a groundwater pollution plume, the flow towards wells or other hydraulic processes are the object of study. In other cases, however, aquifers may be too small spatial units for the purpose in mind. This was evidently the case in the beginning of the 20th century in the USA, when the desire to overview the nation's groundwater resources resulted into Meinzer's 21 groundwater provinces shown in Fig. 3 (Meinzer, 1923). These provinces are relatively large areas having a broad uniformity of hydrogeological and geological conditions. They allow getting a macroscopic picture of groundwater conditions in large territories where many aquifers are present; hence, they are suitable spatial units for communication on groundwater at that scale level. Unlike aquifers, groundwater provinces are not necessarily hydraulically continuous and they represent geographical zones rather than three-dimensional subsurface units. Meinzer's groundwater provinces for the USA have been modified afterwards, first by Thomas and later by Heath (Heath, 1982). Groundwater provinces have been delineated in other parts of the world as well, notably in Australia, where 69 groundwater provinces were identified (Australian government, no date), and in South America that has been subdivided into 16 groundwater provinces (UNESCO and CIAT, 2000).

For presenting, analysing, exchanging, disseminating and discussing groundwater information at a global

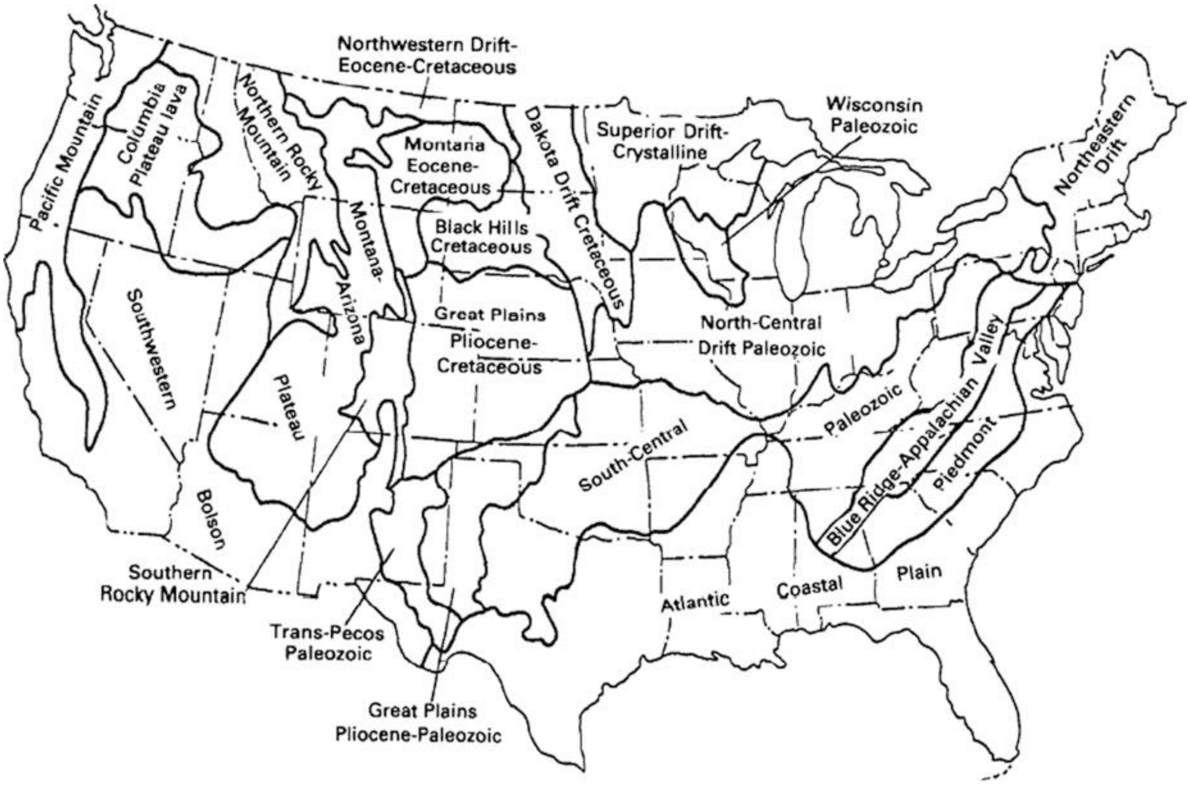


**Fig. 3** Meinzer's groundwater provinces in the conterminous USA (after Meinzer, 1923)

or continental scale, even groundwater provinces may be too small as principal spatial units. At these scale levels it is not unusual to see the information to be aggregated and presented by country or by continent. This has the advantage that the spatial units are well defined and easily recognised. However, for several types of use it has the disadvantage that any relation between national territories and class of groundwater conditions is lacking. Therefore, IGRAC made an attempt to fill this gap by defining so-called global groundwater regions (IGRAC, 2004).

The concept 'river basin' has proven to be extremely useful for information management, analysis and communication in surface water hydrology and water resources management. Especially the use of geographical names – e.g. Nile basin, Amazon basin, Ganges basin – has facilitated an easy common understanding of the areas concerned and certainly has contributed to the general public's knowledge of the geography of water resources. Changes in relevant scale level are accommodated either by subdivision of river basins into sub-basins or by aggregating them into secondary watersheds (e.g. the Mediterranean Sea watershed) or primary watersheds (e.g. the watershed of the Atlantic and Arctic Oceans).

It is believed that scale-dependent worldwide delineation of groundwater systems or zones may produce similar advantages: it will provide a common basis for geo-referenced information management at different scale levels and make groundwater conceptually more accessible by using spatial units or zones with a clear identity. Below, an outline of such an approach to groundwater zoning is presented.

## Methodological Framework and Outcomes of Its Implementation

### General Concepts

Groundwater systems, units or zones are a product of interpretation. Hence they depend on scope and scale, on the available information and on the adopted criteria for delineation and classification. Different sets of criteria will produce different groups of spatial groundwater units. In the approach presented here, the envisaged spatial units were to have time-independent boundaries and to possess each a distinct hydrogeological identity. Consequently, geological and related hydraulic features became principal criteria for delineation. Next, each of the spatial units had to constitute a single continuous body or zone, not a fragmented one. Furthermore, the units defined at different spatial levels should be hierarchically related. Additional scale-specific criteria will be mentioned in the sections below.

The scale-dependent delineation of spatial groundwater units as described here encompasses three different scale levels. These are represented by the following categories of spatial units:

(1) Global groundwater regions (macro-level)
(2) Groundwater provinces (intermediate level)
(3) Aquifers or aquifer systems (local level)

It may be observed that the spatial units at the third level are three-dimensional subsurface bodies, whereas those at the macro-level and intermediate levels rather are geographical zones. However, the three categories of spatial units can be made commensurate easily, either by linking the regions or provinces to the geological formations underneath or by representing the aquifers and aquifer systems by their lateral extent. Each of these categories will be briefly described below.

## Global Groundwater Regions

The concept of global groundwater regions – large territories characterised by a certain dominating hydrogeological setting – was launched and developed by IGRAC. A first subdivision of the Earth (except Antarctica) included 35 global groundwater regions (IGRAC, 2004). After having received comments from several knowledgeable professionals, an amended version now shows 36 such regions (see Fig. 4).

The main purpose of global groundwater regions is to help understanding and memorising major groundwater features and conditions at the global scale. Because of the implicit requirement that people have to memorise where on Earth these regions are located, their number has been kept low (36) and they have received names associated with current geographical names. A basic underlying assumption for delineating these large-sized territories (regions) is that each of them has a characteristic overall groundwater setting contrasting with that of neighbouring regions. Thus, they can be considered as distinct units.

The requirement of keeping the number of global groundwater regions low puts limitations to the degree of uniformity of groundwater conditions within each single region. Nevertheless, the 36 regions roughly can be subdivided into four groups, as indicated by four different colours in Fig. 4:

- Basement regions (red):
  Dominated by geologically very old basement rocks present at or near ground surface. In large part of these regions, groundwater is only present at shallow depths, often in fractures or weathered zones. Stored volumes of groundwater are limited.
- Sedimentary basin regions (yellow):
  Characterised by the occurrence of thick and extensive sedimentary layers that may be permeable to considerable depths. Consequently they may form huge reservoirs. The majority of the groundwater reserves on Earth are located in these regions.
- High-relief folded mountain regions (green):
  In these regions, various types of rocks are arranged in complex structures. In the folded rocks, groundwater occurrence tends to be fragmented and depth to groundwater may vary greatly due to irregular relief. Good aquifer zones are often found in alluvial deposits in valleys and plains.
- Volcanic regions (blue):
  Groundwater in these regions is affected by relatively recent volcanism. Groundwater occurs in porous or fissured lavas and in sediments interbedded between lava flows. Highly permeable zones are not exceptional.

It is reiterated that none of the regions is homogeneous, thus this subdivision only reflects the dominant setting. All regions include sub-regions or zones that have characteristics different from the dominant geological setting. The size of the defined global groundwater regions varies between 15.25 million km$^2$ (Canadian Shield Province) and 0.56 million km$^2$ (Islands of the Pacific), with an average of 4.95 million km$^2$. Summary descriptions of the 36 regions are presented in Appendix 1.

## Groundwater Provinces

Groundwater provinces are conceptually very similar to global groundwater regions, but at a different scale level. Each global groundwater region is subdivided

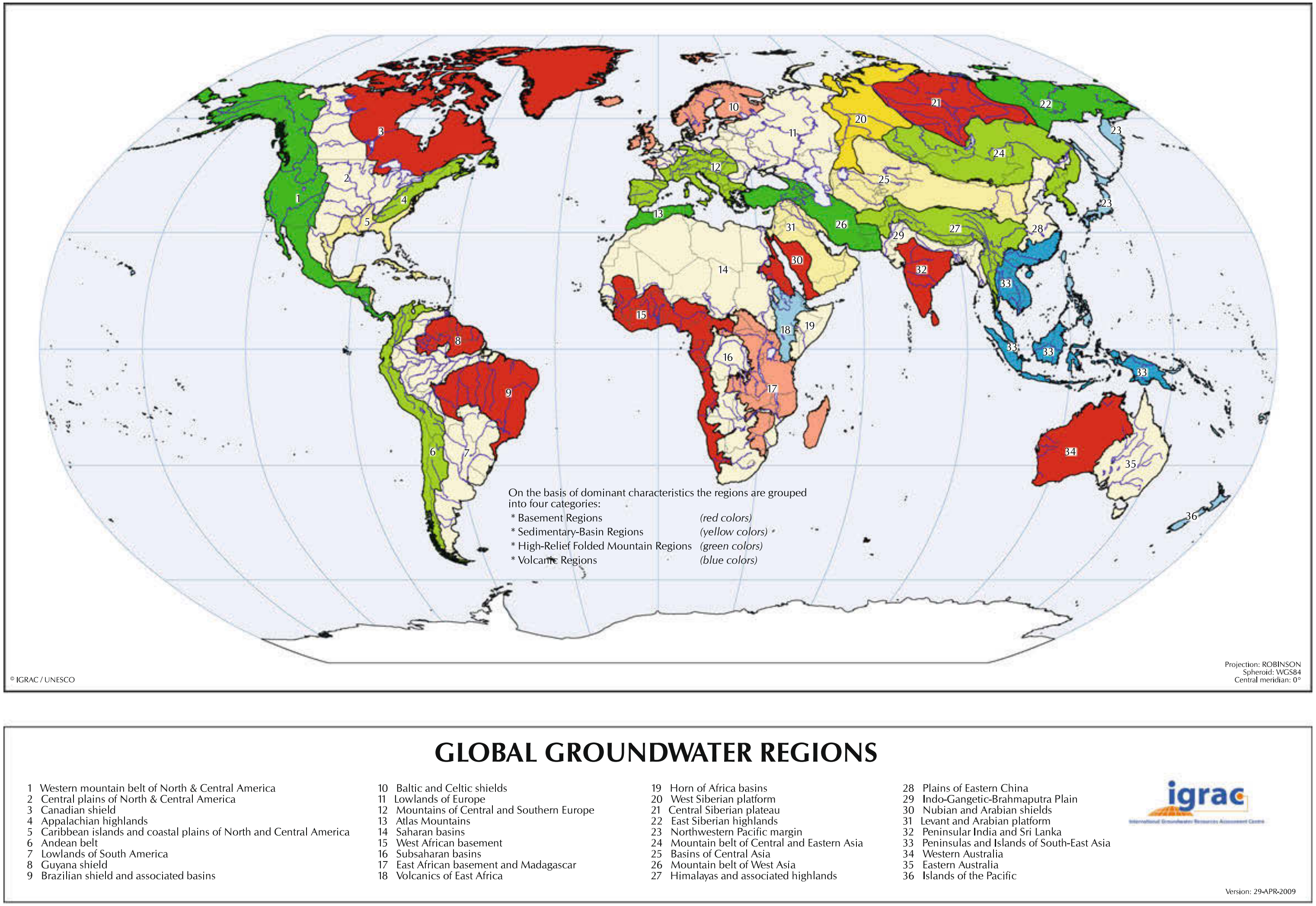


**Fig. 4** Global groundwater regions, as defined by IGRAC (reproduced with permission from IGRAC)

into a number of groundwater provinces (varying from 2 to 18 per region), which allows the latter to be generally more homogeneous than the former ones. Therefore, groundwater provinces have higher resolution and thus are more suitable than global groundwater regions for the characterisation of groundwater conditions at the level of large countries or subcontinents.

As indicated before, groundwater provinces have been defined and are already in use in a number of countries. In its attempt to define groundwater provinces all over the world, IGRAC has respected existing delineations and names, in order to capitalise upon local familiarity with groundwater systems rather than to introduce confusion. Figure 5 shows the resulting provisional map of groundwater provinces, as developed by IGRAC. Maps that facilitate their identification are shown in Appendix 2. Altogether, 217 groundwater provinces have been identified. Their average size is around 0.8 million km$^2$, which is one-sixth of the average size of the global groundwater regions.

## Aquifers and Aquifer Systems

Aquifers and aquifer systems are subsurface bodies defined and partly or completely delineated by individuals and entities involved in the exploration and assessment of groundwater resources. Although the term 'aquifer' tends to be associated with a single geological unit and 'aquifer system' with a complex of such interconnected units, in practice, it is often rather subjective which label to use. For instance, multilayer aquifers and units composed of two different permeable, hydraulically continuous but lithologically distinct layers are called 'aquifers' by some hydrogeologists, whereas other ones would rank them under 'aquifer systems'. Therefore, in this approach to worldwide delineation of groundwater systems, the concepts 'aquifer' and 'aquifer system' are indiscriminately considered to represent the third scale level.

An extremely large number of aquifers and aquifer systems is present in the Earth's subsurface, ranging in areal extent from a few to several millions of square kilometres, and in thickness from a few metres to thousands of metres. Among these, many have been located and explored locally and the most important ones often are identified by a given name. In this approach to scale-dependent zoning, locally identified units and their names are simply adopted as the building stones of the third level of groundwater units. Although aquifers and aquifer systems are three-dimensional bodies, their horizontal projections are zones ('horizontal extent of the aquifer or aquifer system'), sometimes overlapping other aquifer projections.

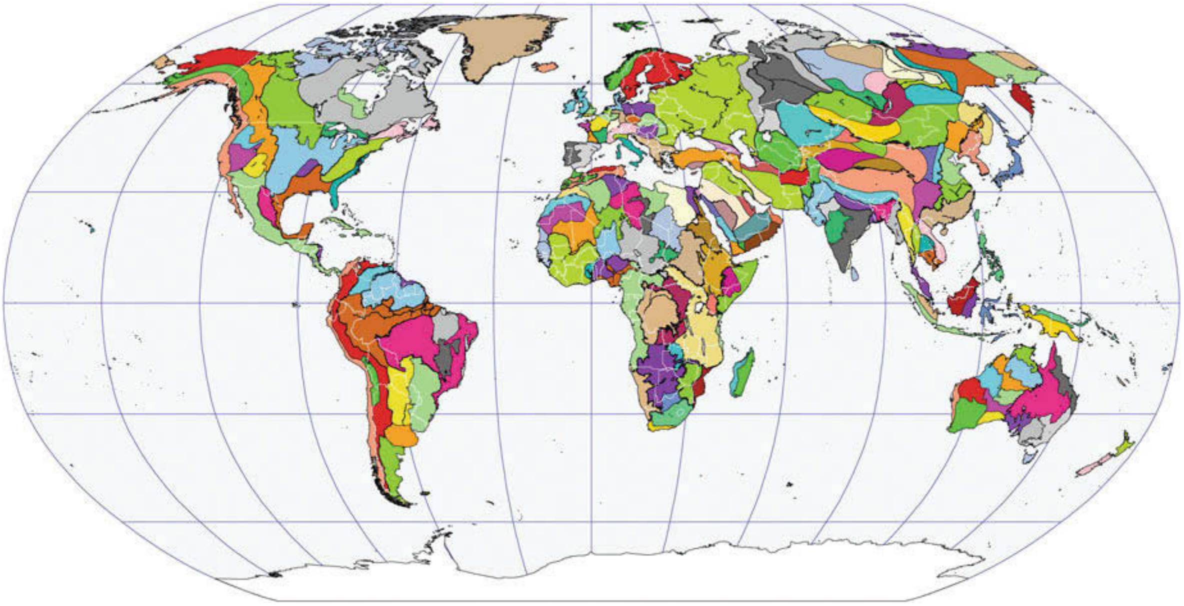


**Fig. 5** IGRAC's provisional delineation of groundwater provinces in the world (reproduced with permission from IGRAC)

The relation between this third level of groundwater units and the next higher level (that of groundwater provinces) is in a few respects different from the relation between the second- and the first-level units. First, whereas each global groundwater region is entirely subdivided into a number of groundwater provinces, only part of the geological formations under each groundwater province is occupied by aquifers or aquifer systems. Many aquifers and aquifer systems are not contiguous with other aquifer systems, but rather are embedded in a non-aquiferous environment. Second, although most aquifers occupy only a fraction of the subsurface under a single groundwater province, there are some exceptions. The first exception is formed by very large aquifer systems, such as the ones shown in Fig. 6. Some of the large aquifer systems (notably numbers 1, 2, 4, 9, 22, 24, 25 and 26) are located indeed within one single global groundwater region, but may occupy more than one groundwater province (Table 1). A second exception is formed by the many narrow alluvial streambed aquifers. They are related to the present-day hydrographic network rather than to the largely geologically based groundwater provinces and global groundwater regions.

### Hierarchical Relationships

Conceptually, the three levels of groundwater zones are hierarchically related: a global groundwater region (first level) consists of a number of groundwater provinces (second level), each of which – in turn – tends to contain a number of aquifers or aquifer systems (third level). On maps this is perfectly reflected for the relation between the first- and second-level zones, as well as for the majority of the aquifers and aquifer systems. However, as pointed out already in the previous section, a minor part of the aquifers or aquifer systems does not fit spatially within one single groundwater province. It is possible to redefine or merge groundwater provinces in order to fit all large aquifer systems, but it is questionable whether the gain in methodological elegance will outweigh the loss of resolution and identification at the groundwater province level. The alluvial riverbed aquifers are unrelated to the global groundwater regions and groundwater provinces, but are closely related to river basins.

## Using the Hierarchically Nested System of Groundwater Zones as an Organising Principle

### Information Management

Information related to groundwater is extremely divers in terms of spatial aggregation. Basic data and derived local information are often representative for only a

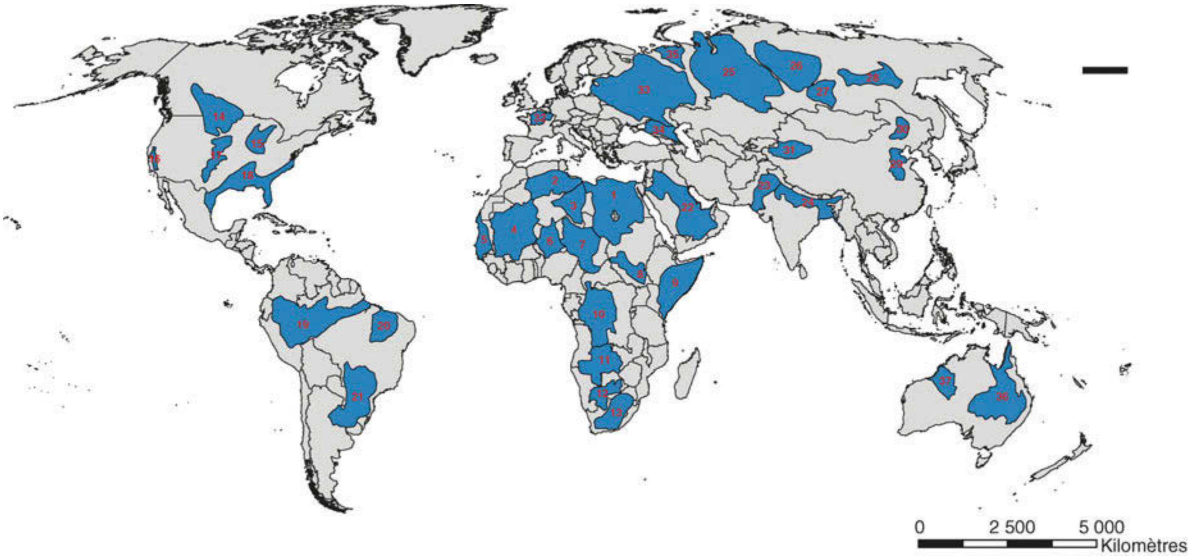


**Fig. 6** The world's largest aquifer systems (Margat, 2008; reproduced with permission from UNESCO, Paris)

**Table 1** Names and approximate lateral extent (in km$^2$) of the large aquifer systems shown in Fig. 6 (after Margat, 2008)

| Continent and aquifer name | Size (km$^2$) |
|---|---|
| **Africa** | |
| 1. Nubian Sandstone aquifer system | 2,199,000 |
| 2. Northern Sahara aquifer system | 1,019,000 |
| 3. Murzuk-Djado basin | 450,000 |
| 4. Taoudeni-Tanezrouft basin | 2,000,000 |
| 5. Senegal-Mauritania basin | 300,000 |
| 6. Iullemeden-Ihrhazer basin | 635,000 |
| 7. Lake Chad basin | 1,917,000 |
| 8. Sudd Basin | 365,000 |
| 9. Ogaden-Juba basin | 1,000,000 |
| 10. Congo basin | 750,000 |
| 11. Upper Kalahari-Zambezi basin | 700,000 |
| 12. Lower Kalahari-Stampriet basin | 350,000 |
| 13. Karoo basin | 600,000 |
| **North America** | |
| 14. Northern Great Plains aquifer system | 2,000,000 |
| 15. Cambrian-Ordovician aquifer system | 250,000 |
| 16. Californian Central Valley aquifer | 80,000 |
| 17. Ogallala aquifer | 450,000 |
| 18. Atlantic and Gulf Coastal plains | 1,150,000 |
| **South America** | |
| 19. Amazon basin | 1,500,000 |
| 20. Maranhão basin | 700,000 |
| 21. Guaraní aquifer system | 1,195,000 |
| **Asia** | |
| 22. Arabian Platform aquifer system | >1,485,000 |
| 23. Indus basin | 320,000 |
| 24. Indus-Ganges-Brahmaputra basin | 600,000 |
| 25. West Siberian basin | 3,200,000 |
| 26. Tunguska basin | 1,000,000 |
| 27. Angara-Lena basin | 600,000 |
| 28. Yakut basin | 720,000 |
| 29. North China Plains aquifer system | 320,000 |
| 30. Songliao plain | 311,000 |
| 31. Tarim basin | 520,000 |
| **Europe** | |
| 32. Paris basin | 190,000 |
| 33. Russian platform | 3,100,000 |
| 34. North Caucasus basin | 230,000 |
| 35. Pechora basin | 350,000 |
| **Australia** | |
| 36. Great Artesian basin | 1,700,000 |
| 37. Canning basin | 430,000 |

very restricted location or subsurface volume – such as the immediate surroundings of a well. Coordinates then tend to be the most suitable means for spatial reference. But if the information is spatially aggregated over larger areas or volumes, then other spatial references will be more convenient. The discussed concepts like aquifers, aquifer systems, groundwater provinces and global groundwater regions offer an opportunity to organise the information – including relevant proxy information as well – in a physically meaningful way at the most appropriate scales. They may become a key element of meta-databases, allow scale-dependent queries or information retrieval and enable scale-dependent processing and reporting on groundwater.

## Enhancing Knowledge

Using zones as presented may be important to enhance local knowledge on groundwater. By their clear identities these zones may contribute to a mental map that helps professionals and other persons in becoming familiar with the geography of groundwater in the area they are interested in, be it at the local level or the more aggregated levels, up to the global level. The geographically oriented zones make it easy to see groundwater occurrence and groundwater properties in the perspective of geological setting. They may also be helpful in identifying and understanding patterns, similarities and interrelations regarding groundwater. The zones as fixed geographical units may form the basis for families of tables or maps showing a large number of attributes, which offers interesting options for comparison and analysis, as well as for the presentation of meaningful indicators. Of course, the availability of good and sufficient data is a prerequisite for doing so.

## Communication and Raising Awareness

Politicians, water managers and the general public tend to have very limited knowledge of groundwater. Information supplied by groundwater professionals often is not absorbed, because people have little notion of what a groundwater system is. The presented zoning system may help. The zones are conceptually simple – provided they are presented with a brief explanation – and easy to memorise because of their geographical names. Once these zones are familiar to the target groups, they become a suitable geographical basis for spreading relevant messages (using indicators and other means). Different zones at different spatial levels allow the messages to be formulated and disseminated at the most appropriate scale.

## Concluding Remarks

The authors believe that groundwater zones with geographically related names and well-defined boundaries may play an important role in organising, deepening and disseminating knowledge on the geography of groundwater systems. The zones provide the backbone for mental images of specific groundwater systems that may be shared between people and that highlight the physical contrasts relevant to groundwater. A simple description of a zone may already evoke a first picture of the physical context (see for instance Appendix 1), which with gradual inclusion of hydrogeological information may evolve into a comprehensive conceptual image of the groundwater conditions in the corresponding area.

At the field level, this has been long understood by hydrogeologists and other professionals who use names to identify the aquifers they explore, study, monitor, develop and manage. From the very moment the aquifer has got a name, it becomes easier to communicate on it and to accumulate and exchange relevant information. At the more aggregated levels (groundwater provinces and global groundwater regions) information is often presented and discussed only on the basis of administrative spatial units such as states, countries and continents. As far as physically oriented groundwater features are concerned, the concepts of groundwater provinces and global groundwater regions may have considerable added value; hence their use is strongly advocated under such conditions.

It seems there is little or no need for centralised coordination of the delineation and nomenclature of aquifers and aquifer systems. These tasks are taken care of more or less spontaneously by local professionals involved. However, the situation is different at the more aggregated spatial levels. The use of groundwater provinces (or zones equivalent to what is called so in this chapter) is limited to a few countries and regions in the world. Global groundwater regions (or equivalents) never have been seen before IGRAC developed the concept. This motivated writing this chapter. If the concepts of ‘groundwater provinces’ and ‘global groundwater regions’ are to produce considerable benefits – and it is believed there is ample scope for it – then the international hydrogeological community should adopt common sets of zones and agree on their delineations and names. The maps showing the global groundwater regions (Fig. 4) and the World's groundwater provinces (Fig. 5 and the maps in Appendix 2), as defined by IGRAC, are a point of departure. It is hoped that interaction within the international community will lead to suggestions for improvement and to gradual convergence to a generally accepted and adopted system of groundwater zones and their names.

## Appendix 1: Brief Description of the Global Groundwater Regions

### North and Central America & The Caribbean

### Global Groundwater Region 1: Western mountain belt of North and Central America

This region, the westernmost zone of the continent, includes highly elevated folded areas of North and Central America, belonging to the Pacific and Cordilleran Belts. Sedimentary and metamorphic rocks underlie the region. After these belts were formed, extensive less deformed basins dominated by volcanic rocks superimposed them. There are large variations in climate: above-average rainfall in mountain zones, low rainfall in arid zones, permafrost conditions in the North and tropical temperature regimes in the South.

The region is subdivided into the following groundwater provinces:

1.01 Alaska
1.02 Cordilleran Orogen of Canada
1.03 Pacific Mountain System
1.04 Columbia Plateau
1.05 Basin and Range
1.06 Colorado Plateau
1.07 Rocky Mountains System
1.08 Central American ranges (including Mexican Sierras)

Groundwater resources are variable. In the mountains they are associated with glacial and fluvial aquifers in faulted troughs or with intermontane basins. The volcanic regions in Central America contain some of the most productive aquifers. Coastal aquifers are present in structural basins filled with marine and alluvial sediments.

### Global Groundwater Region 2: Central plains of North and Central America

This region is located in the heart of North America and includes topographically low areas with gently rolling to flat topography. Except at its Northern edge, there is no boundary with the sea. Thick sequences of sediments deposited in marine, alluvial, glacial and eolian environments cover the Precambrian Basement. Climate is predominantly dry. Permafrost is present in the North.

The region is subdivided into the following groundwater provinces:

2.01 Interior Platform of Canada
2.02 Interior Plains of USA
2.03 Interior Highlands
2.04 Sierra Madre Oriental

Groundwater resources are abundant and the region is characterised by large volumes of stored groundwater. Large regional aquifers occur in porous or fractured consolidated sediments and in large alluvial areas (e.g. High Plains or Ogallala aquifer in USA). Glacial sediments in the Northern parts may form local aquifers.

### Global Groundwater Region 3: Canadian shield

This region includes the low to moderately elevated areas of the Canadian Shield. The region's topography is mainly a result of the effects of glacial action. Precambrian crystalline rocks cover most of the region. Locally remains of sedimentary covers (mainly limestone) are found. Region receives moderate precipitation (often as snow). Continuous permafrost is present in the Northern half.

The region is subdivided into the following groundwater provinces:

3.01 Seven geological provinces of Canadian shield
3.02 Innuitian Orogen
3.03 Hudson Bay Lowlands
3.04 Arctic Platform
3.05 St. Lawrence Platform (including Laurentian Platform of USA)
3.06 Greenland

Groundwater resources are limited. Groundwater is restricted to local pockets of weathered or fractured consolidated rocks or to shallow layers of fluvial and glacial sediments. Certain areas are susceptible to arsenic contamination.

### Global Groundwater Region 4: Appalachian highlands

This region includes the high-elevated Eastern part of North America belonging to the Appalachian Orogenic belt. Metamorphic and igneous rocks are present. After the belt was deformed extensive less deformed basins dominated by sedimentary rocks superimposed it. Climate is predominantly humid.

The region is subdivided into the following groundwater provinces:
4.01 Appalachian Orogen in Canada
4.02 Appalachian Highlands in USA
Groundwater resources are variable. The principal aquifers are found in carbonate rocks and sandstones (e.g. Valley and Ridge aquifers). The high-elevated areas have limited groundwater resources with local surficial aquifer systems in sand and gravel deposits of glacial and alluvial origin.

### Global Groundwater Region 5: Caribbean islands and coastal plains of North and Central America

This region includes the low, flat areas along the Atlantic coast and the Gulf of Mexico, associated with the Ouachita tectonic depression. The coastal plains are huge seawards-thickening wedges of unconsolidated sedimentary rocks lying on consolidated limestone and sandstones. The sediments are of fluvial, deltaic and shallow marine origin. The Caribbean island arc (several thousand islands) is a partially submerged cordillera, having a nucleus of igneous rocks overlain by sediments and volcanics. The region receives abundant precipitation.

The region is subdivided into the following groundwater provinces:
5.01 Atlantic Plains (incl. Florida Peninsula)
5.02 Mexican Gulf Plains (incl. Yucatan Peninsula)
5.03 Caribbean Plains
5.04 Caribbean Islands Arc
Groundwater resources are abundant. Large regional groundwater systems are developed in unconsolidated and (semi-)consolidated sediments (e.g. Coastal lowlands aquifer system and Mississippi River Valley aquifer system). Karst aquifers are frequently found (e.g. Florida and Yucatan aquifer systems). Large islands have combined unconsolidated (alluvial), carbonate and volcanic aquifers. Sea water intrusion is a major problem, especially on islands with shallow freshwater lenses.

## South America

### Global Groundwater Region 6: Andean belt

This region includes the high-elevated areas of South America belonging to the Andean Mobile Belt. There are many wide valleys of tectonic origin and valleys that resulted from fluvial erosion.

The region is composed of heterogeneous rocks. Frequently, a core of granitic and metamorphic rocks is surrounded or partially covered by folded and fractured sedimentary rocks (marine limestone and continental conglomeratic sandstones). On many locations, volcanic rocks (pyroclastic material and lavas) have been ejected or have flowed out. Large variation in climatic conditions is reflected by an above-average rainfall in mountains alternating with arid zones.

The region is subdivided into the following groundwater provinces:
6.01 Andes
6.02 Altiplano
6.03 Coastal
Groundwater resources are variable. Groundwater is typically associated with colluvial aquifers in faulted troughs or basins within mountains. The volcanic zones are very important groundwater sources. High fluoride concentrations are common in these zones. Coastal aquifers occur in structural basins filled with marine and alluvial sediments. These aquifers are prone to seawater intrusions.

### Global Groundwater Region 7: Lowlands of South America

This region includes the low to moderate elevated, flat areas of South American sedimentary basins, relatively unaffected by tectonic events.
Thick sedimentary sequence is composed of consolidated (mainly conglomerates and sandstone) and unconsolidated sediments of alluvial, lacustrine and eolian origin transported from neighbouring high-elevated areas. The region receives moderate to very high precipitation.

The region is subdivided into the following groundwater provinces:
7.01 Orinoco basin (Northern Llanos Basins)
7.02 Amazon basin
7.03 Pantanal and Gran Chaco
7.04 Pampas with Rio de la Plata estuary
7.05 Parana Basin
7.06 Patagonia plains

Groundwater resources are abundant. The unconsolidated alluvial sediments, deposited by the major rivers (e.g. aquifers in the Amazon basin and the Puelches Aquifer) and sandstones (e.g. the Guarani aquifer system) form the most important aquifers. Saline water and high concentrations of arsenic and fluoride are common.

### Global Groundwater Region 8: Guyana Shield

This region includes the moderate elevated, flat topped, Guyana Shield in North-Eastern part of the continent. Crystalline rocks cover almost whole area. The region has a warm and humid climate with annual rainfall in the range of 1000–2000 mm. Groundwater resources are restricted by geological conditions, except for relatively narrow sedimentary zones along the coast. Based on these different hydrogeological conditions, the region is subdivided into two groundwater provinces:

8.01 Guyana Shield province: mainly Precambrian igneous and metamorphic rocks with low potential for storing and transmitting groundwater.
8.02 Guyana Coastal province: deltaic multilayer sandy aquifer systems in the coastal lowlands. They are the main aquifers of the region.

### Global Groundwater Region 9: Brazilian Shield and Associated Basins

This region includes the low to moderate elevated, predominantly flat Brazilian Shield with associated younger sedimentary basins. The Brazilian Shield is mainly composed of crystalline rocks. The associated basins contain a sequence of sandstone, volcanic rocks and unconsolidated sediments. Region receives high precipitation.

The region is subdivided into the following groundwater provinces:

9.01 Brazilian Shield (North, Central, East and South)
9.02 Parnaiba Basin
9.03 Sao Francisco Basin
9.04 Brazilian coastal

Groundwater resources are variable. Groundwater in the crystalline rocks is restricted to local pockets of weathered or fractured zones or to shallow layers of sediments. In the sedimentary basins, both sandstones and unconsolidated sediments can form large aquifers. The volcanic areas (predominantly basalts) have limited groundwater potential.

## Europe

### Global Groundwater Region 10: Baltic and Celtic shield

This region includes the low to moderate elevated, predominantly flat areas of Baltic Shield and Ireland-Scotland Platform. Included are also higher elevated areas of Norwegian Caledonides and Iceland and Massif Armoricain which have more pronounced relief. The Baltic Shield, the Scotland Platform and Massif Armoricain are mainly composed of crystalline rocks. The Ireland Platform is composed of sedimentary rocks, while Iceland is built almost exclusively of young volcanic rocks, predominantly basalts. Region receives medium to high precipitation.

The region is subdivided into the following groundwater provinces:

10.01 Baltic Shield
10.02 Norwegian Caledonides
10.03 Island of Iceland
10.04 Ireland-Scotland Platform
10.05 Massif Armoricain

Groundwater resources are limited. Groundwater in crystalline rocks is restricted to local pockets of weathered or fractured hard rocks. The only widespread aquifers with inter-granular permeability are found in the Quaternary deposits (glacio-fluvial deposits). Local karst aquifers occur in Ireland (e.g. the Waulsortian aquifer). The recent volcanoclastics are highly permeable and can form local aquifers in Iceland.

### Global Groundwater Region 11: Lowlands of Europe

This region includes the low-elevated, flat areas of European sedimentary basins. The higher elevated areas, associated with the Uralian Orogenic Belt, are included in this region as an administrative boundary between Europe and Asia. Thick sedimentary sequence is composed of consolidated and unconsolidated sediments of marine, eolian and alluvial and origin. Region receives medium to high precipitation.

The region is subdivided into the following groundwater provinces:

11.01 Anglo & Paris Basin
11.02 Aquitaine Basin
11.03 London & Brabant Platform
11.04 Dutch Basin
11.05 Northwest German Basin

11.06 German-Polish Basin
11.07 Russian Platform
11.08 Ural Mountains

Groundwater resources are abundant. The unconsolidated sediments form the most important aquifers in the deltas of main rivers (e.g. in the Netherlands). Glacial and eolian aquifers are of local importance. In south-western and northern basins, limestone aquifers are found (e.g. the Chalk Aquifer). The central and eastern parts of the regions have also extensive sandstone aquifers. The Ural Mountains, composed of crystalline rocks, have limited groundwater resources. All coastal aquifers are prone to saline intrusion.

### Global Groundwater Region 12: Mountains of Central and Southern Europe

This region includes the high-elevated areas of Europe belonging to the Hercynian and Alpine Orogenic Belt. Also included are low to medium elevated sedimentary basins associated with these tectonic structures. The folded areas have complex lithology with alternating crystalline, volcanic and sedimentary rocks. Western sedimentary basins contain thick sequence of predominately carboniferous rocks. The eastern basins are covered with thick layers of unconsolidated sediments. Large variations in climate are reflected by an above-average rainfall in mountains alternating with dry zones in the lowlands.

The region is subdivided into the following groundwater provinces:

12.01 Iberian Massifs (a.o. the Hesperian Massif)
12.02 Iberian Basins
12.03 Pyrenees
12.04 Massif Central
12.05 Jura, Vosges and Ardennes
12.06 Southern German Basins
12.07 Alps
12.08 Po Basin
12.09 Apennines
12.10 Bohemian massifs
12.11 Pannonian Basin
12.12 Carpathian Mountains
12.13 Dinaric Alps

Groundwater resources are variable. Groundwater in crystalline rocks is restricted to local pockets of weathered or fractured hard rocks. Alluvial and colluvial fill of relative flat areas form local aquifers in the mountains. In the sedimentary basins, limestone, sandstones and unconsolidated sediments can form large interconnected aquifer systems (e.g. Po Plain aquifers and Hungarian Plain aquifers).

## Africa

### Global Groundwater Region 13: Atlas mountains

This region includes the elevated areas of the Atlas Mountains, created during the Alpine orogenesis in Northwestern Africa. The Northern part is composed of folded sedimentary rocks (mainly limestone). In the Southern part, basement crystalline rocks are covered by shallow marine and alluvial sediments. Precipitation shows large spatial and temporal variation. The Southern areas are subject to desert influences.

The region is subdivided into the following groundwater provinces:

13.01 Northern Atlas mountain range (Anti, High, Middle and Tell Atlas)
13.02 El-Shatout depression
13.03 Saharan Atlas mountains in the South

Groundwater resources are limited to alluvial sediments in the mountains, karstic aquifers in the Northern part and shallow aquifers at the North and North-West coast.

### Global Groundwater Region 14: Saharan basins

This region includes the North African Craton. It comprises a Precambrian basement unconformably overlain by a thick sequence of continental and marine sediments (clastic sediments covered by carbonates), structured into a number of low to medium elevated flat basins separated by higher elevated zones. The flat areas are covered by aeolian sand and locally by alluvial deposits.

The region has an arid climate and is subdivided into the following groundwater provinces:

14.01 Tindoef Basin
14.02 Grand Erg/Ahnet Basin
14.03 Trias/Ghadamedes Basin
14.04 Hamra Basin
14.05 Sirte Basin
14.06 Erdis/Kufra Basin (Nubian sandstone)
14.07 Dakhla Basin (Nubian sandstone)
14.08 Nile valley and delta
14.09 Senegal-Mauritanian Basin
14.10 Regubiat High
14.11 Taoudeni Basin

14.12 Hoggar High
14.13 Iullemeden Basin
14.14 Chad Basin
14.15 Tibesti (Quadai) Mountains
14.16 Ennedi-Darfour Uplift
14.17 Sudan interior basins (Nubian sandstone)
14.18 Ougarta Uplift

Groundwater resources are variable. Groundwater in crystalline rocks is restricted to local pockets of weathered or fractured zones or to shallow layers of fluvial sediments. In the sedimentary basins sandstone and limestone layers form important regional aquifer systems. Some of these aquifers are deep and receive no modern recharge (e.g. The Nubian Sandstone Aquifer). Other systems are recharged in the river valleys (e.g. Iullemeden Aquifer System). Large alluvial aquifers developed along the river Nile and in its delta.

### Global Groundwater Region 15: West African basements

This region includes low to moderate elevated, flat areas of the West African Shield and sedimentary basins associated with large rivers. Narrow coastal strip containing unconsolidated sediments is also included. The Shield areas are dominated by outcropping crystalline Basement rocks. Region has a humid climate in the Northern parts along the coast and a dry climate in the South and the Northern strip along the Sahara.

The region is subdivided into the following groundwater provinces:

15.01 Eburneen Massif
15.02 Volta Basin
15.03 Niger Delta
15.04 Nigerian Massif
15.05 West Congo Precambrian Belt
15.06 Damer Belt

Some areas have high fluoride concentrations. Deltas of large rivers (Volta, Niger) have more favourable groundwater conditions. High arsenic concentrations are found locally.

### Global Groundwater Region 16: Sub-Saharan basins

This region includes large inland depressions in basement rocks of Central and Southern Africa that have been filled by sediments of various origins. The sedimentary areas are moderate elevated and have flat relief. Topographical high of crystalline rocks, which separate two Southern basins, is included in this region. Region has a humid climate in the Northern parts and a dry climate in the South. Groundwater resources are abundant.

The region is subdivided into the following groundwater provinces:

16.01 Congo basin
16.02 Kalahari-Ethosha Basin
16.03 Kalahari Precambrian Belt
16.04 Karoo Basin
16.05 Cape Fold Belt
16.06 Coastal Basins of Mozambique

Large regional aquifers are found in unconsolidated sediments (e.g. in Congo basin) and fractured sandstones (e.g. Karoo Aquifer system). Limestone and dolomite layers (e.g. Katanga System) form local aquifers. Shales and crystalline rocks are poor aquifers. Some of the aquifers receive limited modern recharge.

### Global Groundwater Region 17: East African basement and Madagascar

This region includes moderate elevated, flat areas of the East African Shield, affected in the Eastern parts by rifting. The region is dominated by outcropping crystalline Basement rocks, with local occurrence of volcanic rocks and sediments. Climate is humid in the Northern parts and dry in the South. Groundwater resources are limited.

The region is subdivided into the following groundwater provinces:

17.01 East Congo Precambrian Belt
17.02 Luffilian Arch (Katanga system)
17.03 East Kalahari Precambrian Belt
17.04 East Africa Basement (including rifted zones)
17.05 Tanzania coastal basin
17.06 Sediments of Madagascar
17.07 Basement of Madagascar

Groundwater resources are limited. Groundwater in crystalline rocks is restricted to local pockets of weathered or fractured zones or to shallow layers of fluvial sediments. Coastal sediments (e.g. Karoo Sandstone in Tanzania) have favourable groundwater conditions. High fluoride concentrations occur locally.

### Global Groundwater Region 18: Volcanics of East Africa

This region includes the moderate to high-elevated part of the East African Craton that has been affected by rifting and volcanism. In the rifted zone, large fault escarpments and steep slopes of volcano's dominate the relief. Arid to semiarid climate prevails, with humid zones in higher elevated areas. Groundwater resources are variable.

The region is subdivided into the following groundwater provinces:
18.01 Amhara Plateau
18.02 Eastern Branch of East African Rift Valley

Groundwater in crystalline rocks is restricted to local pockets of fractured and weathered zones or shallow layers of alluvial sediments. In volcanic areas groundwater occurs in fractured zones and in the sediments interbedded between successive lava flows ('old land surfaces'). Groundwater may contain high concentrations of fluoride and is often hot and brackish in the Rift Valley.

### Global Groundwater Region 19: Horn of Africa basins

This region includes large depressions in basement rocks that have been filled by sediments of various origins. Locally isolated uplifted Basement complexes occur. Southern en central parts are flat and moderate-elevated. Northern parts have more pronounced relief. Arid to semiarid climate prevails, with humid zones in higher elevated areas. Groundwater resources are variable.

The region is subdivided into the following groundwater provinces:
19.01 Ogaden Basin
19.02 Somali Coastal Basin

Groundwater resources are variable. Groundwater in crystalline rocks is restricted to local pockets of fractured and weathered zones or shallow layers of alluvial sediments. The sedimentary rocks have variable groundwater potential. Sandstones and fractured limestones are permeable and have good yields, although water levels are in place deep. Interbedded silt and clay horizons form barriers to groundwater flow. The best aquifers are found in coarse Quaternary alluvial sediments in the floodplains of major rivers. Dissolution of evaporates occurring in central horizons of sediments causes increased salinity of groundwater.

## Asia

### Global Groundwater Region 20: West Siberian platform

This region includes the low to moderate elevated, flat areas of West Siberian craton that has been rifted and filled by thick sedimentary sequences. Upper part of these sequences consists predominantly of alluvial-lacustrine sediments. Climate is cold and dry. In the Northern parts of the region is a belt of permafrost. Groundwater resources are abundant.

The region is subdivided into the following groundwater provinces:
20.01 Yenisey Basin
20.02 West Siberian Basin
20.03 Turgay Depression (basin)

Groundwater resources are abundant. Unconsolidated sediments show large variations in grain size. Main aquifers are associated with layers of coarse material in alluvial sediments. Fractured sandstones form local aquifers.

### Global Groundwater Region 21: Central Siberian plateau

This region includes the moderate elevated areas of Central Siberian craton, including large basins separated by uplifted highs and arches of crystalline rocks. Numerous rivers have further modified the relief of the region. Climate is cold and dry. In the Northern half of the region is a belt of permafrost.

The region is subdivided into the following groundwater provinces:
21.01 Tunguska Basin
21.02 Cis-Sayan Basin
21.03 Lena-Vilyuy Basin
21.04 Anabar-Olenek High
21.05 Nepa-Botuoaba Arch
21.06 Aldan uplift

Groundwater resources are moderate. Alluvia associated with large rivers (e.g. Lena) and fissured limestone and sandstones form potential aquifers. Crystalline rocks have a low groundwater potential restricted to weathered zones. Groundwater distribution is greatly influenced by permafrost.

### Global Groundwater Region 22: East Siberian highlands

This region includes the moderate to high-elevated areas of East Siberian craton. The craton now is largely covered by thick sedimentary sequences of marine and continental sediments. The relief of the region is related to anticlinal structures in sedimentary rocks. In the Eastern parts of the region, also crystalline rocks crop out in the folded structures. Climate is cold and dry. Almost entire region belongs to the permafrost zone.

The region is subdivided into the following groundwater provinces:

22.01 Verkhoiansk Range
22.02 Cherskii Range
22.03 Kolyma Plain
22.04 Yukagir Plateau
22.05 Anadyr Range

Groundwater resources are limited. Groundwater occurrence is restricted to fractured or weathered zones in crystalline rocks and consolidated sediments. Locally aquifers in unconsolidated alluvial sediments may occur. Groundwater distribution is greatly influenced by permafrost.

### Global Groundwater Region 23: Northwestern Pacific margin

This region includes the moderate to high-elevated areas of Northwestern Asia associated with the unstable island arch of West Pacific (Circum-Pacific Belt). These areas have pronounced relief, related to uplift of sedimentary rocks and volcanic activity. The sedimentary formations consist mainly of marine sandstones and mudstones, which are intercalated by limestone and granitic intrusions. The climate varies from cold and dry to hot and moist.

The region is subdivided into the following groundwater provinces:

23.01 Kamchatka Peninsula
23.02 Kuril Islands
23.03 Japan
23.04 Philippines

Groundwater occurs in fractured and fissured sandstones and limestone. Porous volcanic rocks and locally thick unconsolidated sediments form productive aquifers (e.g. Tokyo Group Aquifer System). Thermal zones, associated with volcanic activity, affect the groundwater composition.

### Global Groundwater Region 24: Mountain belt of Central and Eastern Asia

This region includes the high-elevated areas of Central and East Asia associated with Palaeozoic Mobile Belt. As result of intensive folding, the region has a steep relief. Crystalline rocks dominate the surface in the Northern half of the region. In the Southern half, crystalline and volcanic rocks alternate with consolidated and unconsolidated sediments.

The region is subdivided into the following groundwater provinces:

24.01 The Altay-Sayan Folded Region (Central Siberia-Mongolia Border)
24.02 Mongol-Okhotsk Folded Region
24.03 Baikal-Paton Folded Region (surroundings of Lake Baikal)
24.04 Aldan Shield in Eastern Siberia
24.05 Yinshah Da and Xia Hinggannling Uplift (Yablonovy and Khingan ranges)
24.06 Sikhote-Alin Folded Region (South-East Siberia)
24.07 Korean Peninsula

Groundwater resources are limited to moderate. Local aquifers occur in intermontane alluvial systems, fractured volcanic rocks, and karstified carbonates. Crystalline rocks have a low groundwater potential, restricted to the thickness of the weathered zone. Highlands have low precipitation and high evaporation, while coastal areas have a moist climate. Groundwater resources are limited to moderate.

### Global Groundwater Region 25: Basins of Central Asia

This region includes the low to moderate elevated, relatively flat areas of West and Central Asia. Low-elevated Western part of the region is associated with huge geo-syncline containing a thick sequence of sedimentary rocks. In Western parts, the sedimentary basins are separated by more elevated areas containing crystalline rocks. Unconsolidated alluvial and eolian deposits cover large areas. Climate is arid to semiarid.

The region is subdivided into the following groundwater provinces:

25.01 Central Kazakhstan Folded Region
25.02 Syr-Darya basin
25.03 Tian Shan Foldbelt
25.04 Junggar Basin
25.05 Tarim Basin
25.06 Altushan Fold Belt
25.07 Jinguan Minle Wuwei Basin
25.08 Ordos Basin
25.09 Shauxi Plateau
25.10 Taihang Shan Yanshan Fold Belt

Groundwater resources are variable. Regional aquifers occur in fractured sandstones, karstified limestone (e.g. Erdos Basin aquifer) and alluvial sediments. Groundwater in extensive loess deposits is associated with the presence of permeable paleo-soils. These horizons are an important water source. Modern recharge is very limited.

### Global Groundwater Region 26: Mountain belt of West Asia

This region includes high-elevated areas of West Asia, belonging to the Alpine-Himalayan Mobile Belt (Taurus Mountains, Anatolian Plateau, Caucasus, Central Iranian Basins, Elburz Mountains and Zagros Fold belt and Trust zone). Also included are medium elevated sedimentary basins associated with tectonic structures. The folded areas have complex lithology with alternating crystalline, volcanic and sedimentary rocks. Sedimentary depressions containing predominately marine sediments (carboniferous rocks and sandstones). Basins are locally covered with thick layers of unconsolidated sediments. Climate is predominantly dry, with some moist zones in the higher altitudes.

The region is subdivided into the following groundwater provinces:

26.01 Taurus Mountains
26.02 Anatolian Plateau
26.03 Caucasus
26.04 Central Iranian Basins
26.05 Elburz Mountains
26.06 Zagros Fold belt and Trust zone (Zagros Mountains)

Groundwater resources are low to moderate. Alluvial and colluvial fill of relative flat areas form local aquifers in the mountains. In the sedimentary basins, karstified limestone (e.g. Midyat Aquifer in Turkey) are major groundwater sources. Fractured sandstones and unconsolidated sediments can also form interconnected aquifer systems. The groundwater yield of unconsolidated sediments is high in the alluvial deposits directly connected to the riverbeds.

### Global Groundwater Region 27: Himalayas and associated highlands

This region includes high-elevated areas of Central Asia, belonging to the Himalayan Mobile Belt. It is continuation of the West Asian part of this belt (Region 26). The folded areas have complex lithology with altering crystalline, volcanic and sedimentary rocks. Climate varies from warm and humid to cold and arid. Large areas are covered by glaciers or seasonal snow.

The region is subdivided into the following groundwater provinces:

27.01 Hindu Kush
27.02 Pamir High
27.03 Tibetan Plateau
27.04 Himalayas
27.05 Sichuan Basin
27.06 Tenasserim Mountains

Groundwater resources are limited. Alluvial and colluvial fills in relative flat areas might form extensive aquifers (e.g. Kathmandu Valley) in the mountains. Local aquifers also occur in karstic limestone and fractured sandstones.

### Global Groundwater Region 28: Plains of Eastern China

This region includes the low to medium elevated areas of Great Plains of Eastern China. Thick sequences of alluvial and aeolian sediments were deposited in sedimentary basins. Region receives low to medium precipitation.

The region is subdivided into the following groundwater provinces:

28.01 Manchurian Plain
28.02 North China Plain
28.03 Middle and Lower Chang Jiang (Yangtze) River Basin

Groundwater resources are abundant. Extensive alluvial aquifers (e.g. Huang-Hai-Hai Plain) store large volumes of groundwater. This region obtained its separate status also due to a very high population density. The bulk of the population of East Asia lives in this region.

### Global Groundwater Region 29: Indo-Gangetic-Brahmaputra plain

This region includes the low elevated and flat reaches of large Asian rivers draining the Himalayas. Thick layers of sediments accumulated in the foredeep, which underlie the Ganges Plain and neighbouring plains. Climate varies from arid to humid as the mean annual rainfall increases from west to east.

The region is subdivided into the following groundwater provinces:

29.01 Indus Basin
29.02 Ganges Basin
29.03 Brahmaputra Basin
29.04 Irrawaddy Basin

Groundwater resources are abundant. Extensive alluvial aquifer system, associated with major rivers draining the Himalayas, is one of the largest groundwater reservoirs in the world.

### Global Groundwater Region 30: Nubian and Arabian shields

This region includes the low-elevated coastal plains, associated with the Red Sea depression, and moderate high areas belonging to the Nubian and Arabian Shields. High-elevated, rift-related, volcanic areas are also included in this region. Climate is arid to semiarid. Red Sea Hills in Africa (including parts of Sahara and Ethiopian Highlands).

The region is subdivided into the following groundwater provinces:

30.01 Red Sea Hills in Africa
30.02 Red-Sea coastal plains (e.g. Tihama Plains)
30.03 North Western Escarpment Mountains (Midian & Hiraz)
30.04 Asir Mountains
30.05 Arabian Shield (e.g. Najd Plateau)
30.06 Yemen Highlands

Groundwater resources are variable. Crystalline rock areas have limited groundwater potential, restricted to local weathered zones. Larger aquifer systems are associated with unconsolidated sediments underlying plains (e.g. Tihama aquifer) and river deltas (e.g. Abyan). Fractured sandstones, limestone and volcanic rocks, underlying the Yemeni Highlands, can form important aquifers.

### Global Groundwater Region 31: Levant and Arabian platform

This region includes the low to moderate elevated, predominantly flat areas of the Levant region and Western parts of the Arabian Peninsula. More elevated areas in Oman are also included. Large rift basins were successively filled with sediments of different origin. Climate is arid.

The region is subdivided into the following groundwater provinces:

31.01 Sinai
31.02 Euphrates-Tigris Basin
31.03 Al Hasa Plain in (Saudi Arabia)
31.04 Central Arch with Tuwaig Mountains
31.05 Rub Al Khali Basin
31.06 Marib and Shabwa basins in Yemen
31.07 Masila-Jeza Basin (with wadi Hadramawt)
31.08 Mountains and plains of Oman

Groundwater resources are abundant in terms of stored volumes, but limited in terms of replenishment. Large regional aquifer systems are found in sandstones (e.g. Mukalla Aquifer System) and fissured carbonates (e.g. Umm-Er-Rhaduma Aquifer System). Unconsolidated alluvial sediments along main wadis form local aquifers.

### Global Groundwater Region 32: Peninsular India and Sri Lanka

This region includes low- to moderate-elevated areas of the Indian craton. The region is predominantly composed of crystalline rocks. Volcanic (basalt) rocks belonging to the Deccan Trap cover a large area in the Western part of the peninsula. In coastal areas, sedimentary rocks (predominantly sandstones) occur. These rocks might be covered by thick accumulation of unconsolidated sediments especially in the deltas of larger rivers. Climate varies from arid to humid.

The region is subdivided into the following groundwater provinces:

32.01 Precambrian basement areas in southern and eastern India
32.02 Precambrian basement area of Aravalli Range in Rajasthan
32.03 Precambrian basement and sediments of Sri Lanka
32.04 Deccan Trap
32.05 Coastal sedimentary areas

Groundwater resources are low to moderate. Groundwater in crystalline rocks is restricted to local pockets of fractured and weathered zones or shallow layers of alluvial sediments. Sedimentary intercalations between lava flows (intertrappeans) are important groundwater sources in volcanic areas. Major deltaic and coastal aquifers, particularly along the East coast, have the highest potential. The coastal zones are prone to seawater intrusion.

### Global Groundwater Region 33: Peninsulas and Islands of South-East Asia

This region includes low- to moderate-elevated areas of peninsulas and islands of South-East Asia associated with the Circum-Pacific Belt. Tectonic activity in this area produces a complex geological setting. The region is characterised by outcrops of old crystalline rocks, deep sedimentary basins and recent volcanic eruptions. Climate is humid.

The region is subdivided into the following groundwater provinces:

33.01 South China Fold Belt
33.02 Truong Son Fold Belt
33.03 Thailand Basin
33.04 Khorat Platform
33.05 Tonle Sap-Phnom Penh Basin
33.06 Malay Peninsula
33.07 Sumatra/Java Magmatic Belt
33.08 Sumatra Basin
33.09 Sunda Platform
33.10 Barito-Kutei Basin
33.11 Sulawesi Magmatic Arc
33.12 Irian Basins
33.13 New Guinea Mobile Belt

Groundwater resources are variable. Groundwater in crystalline and volcanic rocks is restricted to local pockets of fractured and weathered rocks. Unconsolidated sediments (e.g. in Jakarta Groundwater basin) and fissured sedimentary rocks (e.g. karstic zones in Vietnam) form regional aquifers. The groundwater in volcanic areas has a high fluoride content.

## Australia & The Pacific

### Global Groundwater Region 34: Western Australia

This region includes low to moderate elevated, predominantly flat basement blocks of Australian Craton, separated by deep sedimentary basins. Sedimentary basins contain thick layers of sandstones and karstified limestone and local alluvial sediments. Climate is semiarid to arid.

The region is subdivided into the following groundwater provinces:

34.01 Pilbara Block
34.02 Yilgarn Basement Block
34.03 Carnarvon Basin
34.04 Canning Basin
34.05 Officer Basins
34.06 Eucla Basin
34.07 Kimberly Basement Block
34.08 Musgrave Basement Block
34.09 McArthur Basin
34.10 Wiso and Georgina Basins

Groundwater resources are low to moderate. Groundwater in crystalline and volcanic rocks is restricted to local pockets of fractured and weathered zones or shallow layers of alluvial sediments. Fissured sandstones (e.g. Canning Basin) and limestone (e.g. Eucla Basin) form large regional aquifers. The amount of renewable groundwater is small in comparison to the total storage. Palaeochannel sands (representing former riverbeds) are also prospective aquifers in the region, though the groundwater salinity is high.

### Global Groundwater Region 35: Eastern Australia

This region includes low- to moderate-elevated, flat areas of East Australian sedimentary basins. The older consolidated sediments are frequently overlain by extensive alluvial fans. Uplifted areas in the Eastern margin (Great Dividing Range), belonging to the Tasman Mobile Belt, are also included. Climate is arid to semiarid.

The region is subdivided into the following groundwater provinces:

35.01 Gawler Ranges
35.02 Great Artesian Basin
35.03 Murray Basin
35.04 Great Dividing Range
35.05 Australian Alps
35.06 Tasmania Island

Groundwater resources are moderate to high. Thick layers of sandstones form one of the world's largest aquifer systems (The Great Artesian Basin Aquifer System). Fissured limestone aquifers also occur (e.g. Murray Group Aquifer). Extensive alluvial aquifers, associated with the large rivers draining the uplifted areas, are important shallow groundwater source. Uplifted areas themselves have only local aquifers found in the fractured rocks.

### Global Groundwater Region 36: Islands of the Pacific

This region includes small islands of South-Eastern Pacific and New Zealand, belonging to the Circum-Pacific Belt. Pacific islands West of the American continents are also included. The region has large variation in elevation and relief. Volcanic rocks are found in the Northern part. The Southern part (New Zealand) includes also crystalline rocks, uplifted by orogeny, and thick sequences of sedimentary rocks. Climate is humid.

The region is subdivided into the following groundwater provinces:

36.01 Bismarck -New Hebrides Volcanic Arcs
36.02 Fiji Islands

36.03 Orogenic belt of New Caledonia
36.04 Axial tectonic belt of New Zealand
36.05 Sedimentary basins of New Zealand
36.06 Pacific islands West of the American continents

Groundwater resources are variable. Some recent volcanic rocks are highly porous and contain large volume of water. Karstified limestone and porous calcareous formations in coastal areas are also important aquifers. Shallow aquifers occur in unconsolidated alluvial sediments. Freshwater lenses are usually shallow and saline water intrusions are very common.

## Appendix 2: Proposed Groundwater Provinces

(See Figs. 7, 8, 9, and 10)

### WESTERN MOUNTAIN BELT OF NORTH & CENTRAL AMERICA

1.01 Alaska
1.02 Cordilleran Orogen of Canada
1.03 Pacific Mountain System
1.04 Columbia Plateau
1.05 Basin and Range
1.06 Colorado Plateau
1.07 Rocky Mountains System
1.08 Central American Ranges

### CENTRAL PLAINS OF NORTH & CENTRAL AMERICA

2.01 Interior Platform of Canada
2.02 Interior Plains of the USA
2.03 Interior Highlands
2.04 Sierra Madre Oriental

### CANADIAN SHIELD

3.01 Seven geological Provinces of the Canadian Shield
3.02 Innuitian Orogen
3.03 Hudson Bay Lowlands
3.04 Arctic Platform
3.05 St. Lawrence Platform
3.06 Greenland

### APPALACHIAN HIGHLANDS

4.01 Appalachian Orogen in Canada
4.02 Appalachian Highlands in the USA

### CARIBBEAN ISLANDS AND COASTAL PLAINS OF NORTH AND CENTRAL AMERICA

5.01 Atlantic Plains
5.02 Mexican Gulf Plains
5.03 Caribbean Plains
5.04 Carribean Islands Arc

### ANDEAN BELT

6.01 Andes
6.02 Altiplano
6.03 Coastal

### LOWLANDS OF SOUTH AMERICA

7.01 Orinoco Basin
7.02 Amazon Basin
7.03 Pantanal and Gran Chaco
7.04 Pampas with Rio de la Plata Estuary
7.05 Parana Basin
7.06 Patagonia Plains

### GUYANA SHIELD

8.01 Guyana Shield
8.02 Gyuana Coastal

### BRAZILIAN SHIELD AND ASSOCIATED BASINS

9.01 Brazilian Shield
9.02 Parnaiba Basin
9.03 Sao Francisco Basin
9.04 Brazilian Coastal

### BALTIC AND CELTIC SHIELDS

10.01 Baltic Shield
10.02 Norwegian Caledonides
10.03 Island of Iceland
10.04 Ireland-Scotland Platform
10.05 Massif Armoricain

### LOWLANDS OF EUROPE

11.01 Anglo and Paris Basin
11.02 Aquitaine Basin
11.03 London and Brabant Platform
11.04 Dutch Basin
11.05 Northwest German Basin
11.06 German-Polish Basin
11.07 Russian Platform
11.08 Ural Mountains

### MOUNTAINS OF CENTRAL AND SOUTHERN EUROPE

12.01 Iberian Massif
12.02 Iberian Basins
12.03 Pyrenees
12.04 Massif Central
12.05 Jura, Vosges and Ardennes
12.06 Southern German Basin
12.07 Alps
12.08 Po Basin
12.09 Appennines
12.10 Bohemian Massif
12.11 Pannonian Basin
12.12 Carpathian Mountains
12.13 Dinaric Alps

### ATLAS MOUNTAINS

13.01 Northern Atlas Mountains
13.02 El-Shatout Depression
13.03 Saharan Atlas Mountains

### SAHARAN BASINS

14.01 Tindoef Basin
14.02 Grand Erg/Ahnet Basin
14.03 Trias/Ghadamedes Basin
14.04 Hamra Basin
14.05 Sirte Basin
14.06 Erdis/Kufra Basin
14.07 Dakhla Basin
14.08 Nile Valley and Delta
14.09 Senegal Mauretanian Basin
14.10 Regubiat High
14.11 Taoudeni Basin
14.12 Hoggar High
14.13 Iullemeden Basin
14.14 Chad Basin
14.15 Tibesti (Quadai) Mountains
14.16 Ennedi-Darfour Uplift
14.17 Sudan Interior Basins
14.18 Ougarta Uplift

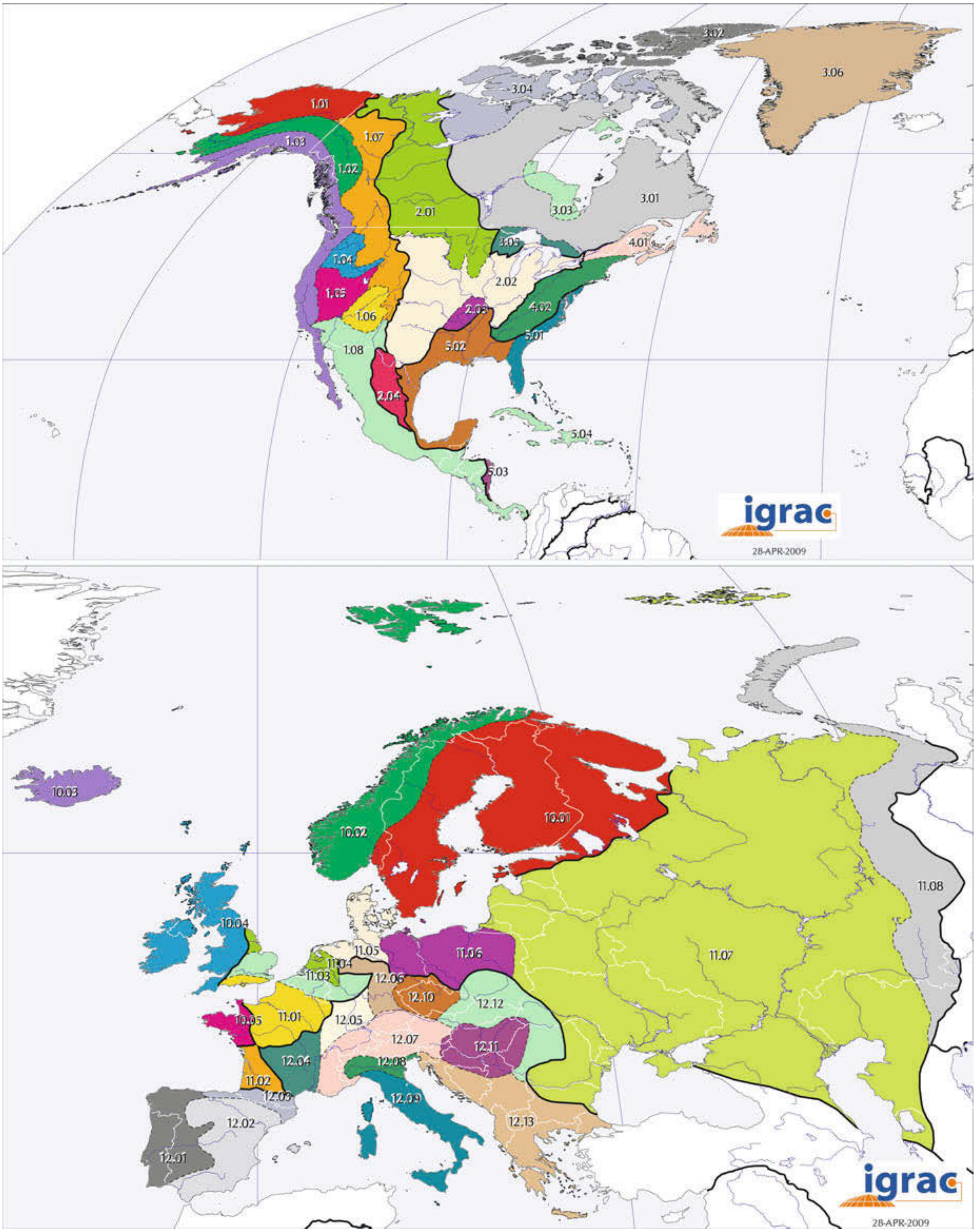


**Fig. 7** Groundwater provinces in North & Central America and in Europe (reproduced with permission from IGRAC)

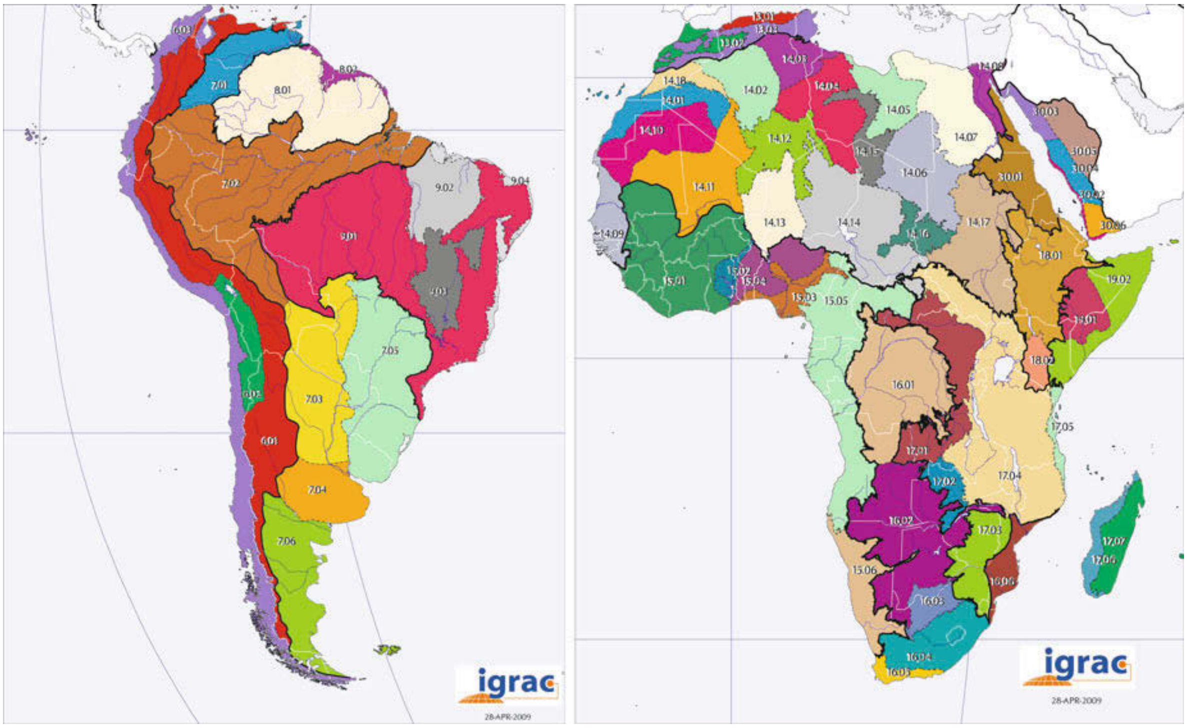


**Fig. 8** Groundwater provinces in South America and in Africa (reproduced with permission from IGRAC)

### WEST AFRICAN BASEMENT

15.01 Eburneen Massif
15.02 Volta Basin
15.03 Niger Delta
15.04 Nigerian Massif
15.05 West Congo Precambrian Belt
15.06 Damer Belt

### SUB-SAHARAN BASINS

16.01 Congo Basin
16.02 Kalahari-Etosha Basin
16.03 Kalahari Precambrian Belt
16.04 Karoo Basin
16.05 Cape Fold Belt
16.06 Coastal Basins of Mozambique

### EAST AFRICAN BASEMENT AND MADAGASCAR

17.01 East Congo Precambrian Belt
17.02 Luffillian Arch
17.03 East Kalahari Precambrian Belt
17.04 East Africa Basement
17.05 Tanzania Coastal Basin
17.06 Sediments of Madagascar
17.07 Basement of Madagascar

### VOLCANICS OF EAST AFRICA

18.01 Amhara Plateau
18.02 Eastern Branch of East African Rift Valley

### HORN OF AFRICA BASINS

19.01 Ogaden Basin
19.02 Somali Coastal Basin

### WEST SIBERIAN PLATFORM

20.01 Yenisey Basin
20.02 West Siberian Basin
20.03 Turgay Depression

### CENTRAL SIBERIAN PLATEAU

21.01 Tunguska Basin
21.02 Cis-Sayan Basin
21.03 Lena-Vilyuy Basin
21.04 Anabar-Olenek High
21.05 Nepa-Botuoba Arch
21.06 Aldan Uplift

### EAST SIBERIAN HIGHLANDS

22.01 Verkhoiansk Range
22.02 Cherskii Range
22.03 Kolyma Plain
22.04 Yukagir Plateau
22.05 Anadyr Range

### NORTHWESTERN PACIFIC MARGIN

23.01 Kamchatka Peninsula
23.02 Kuril Islands
23.03 Japan
23.04 Philippines

### MOUNTAIN BELT OF CENTRAL AND EASTERN ASIA

24.01 The Altay-Sayan Folded Region

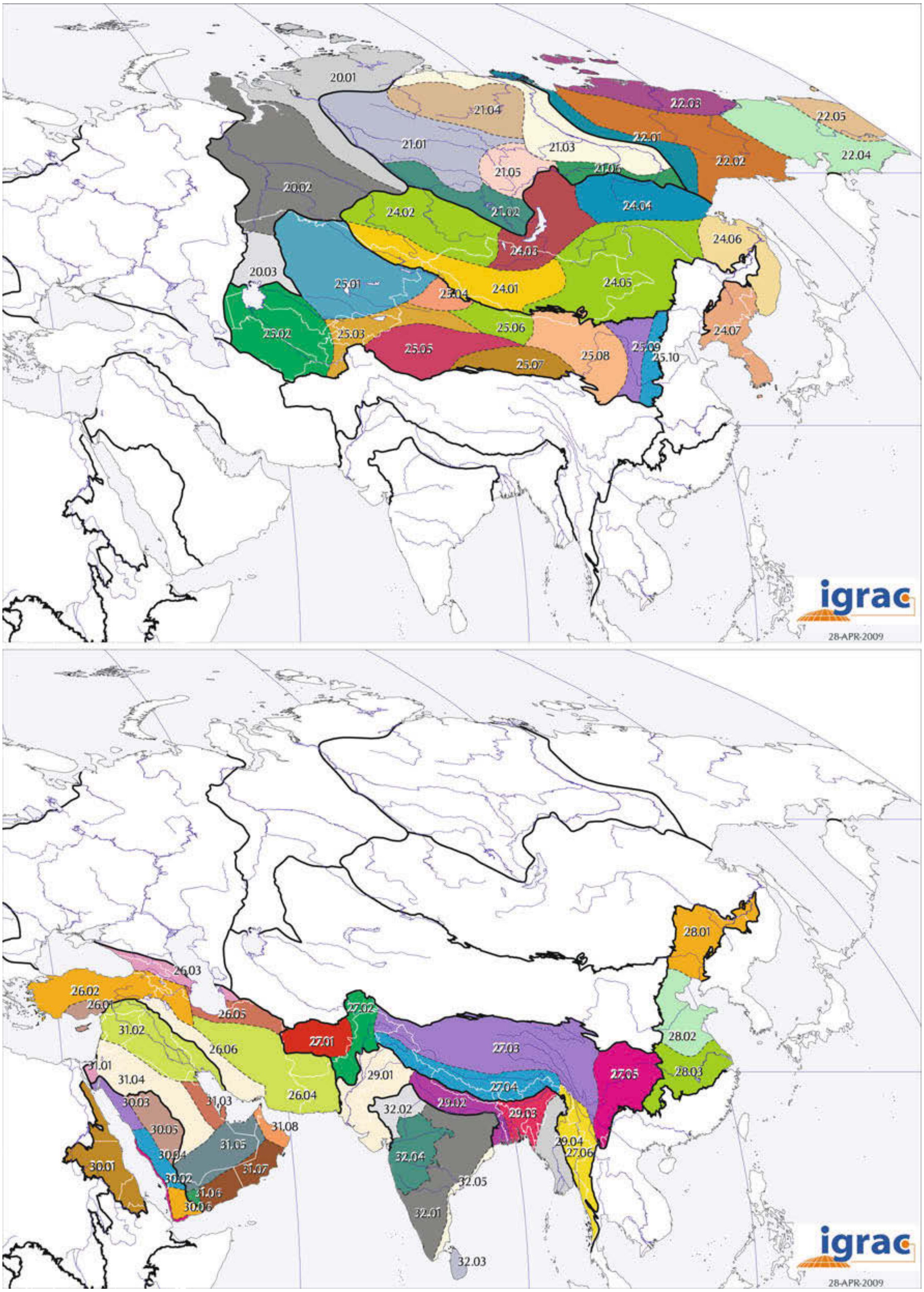
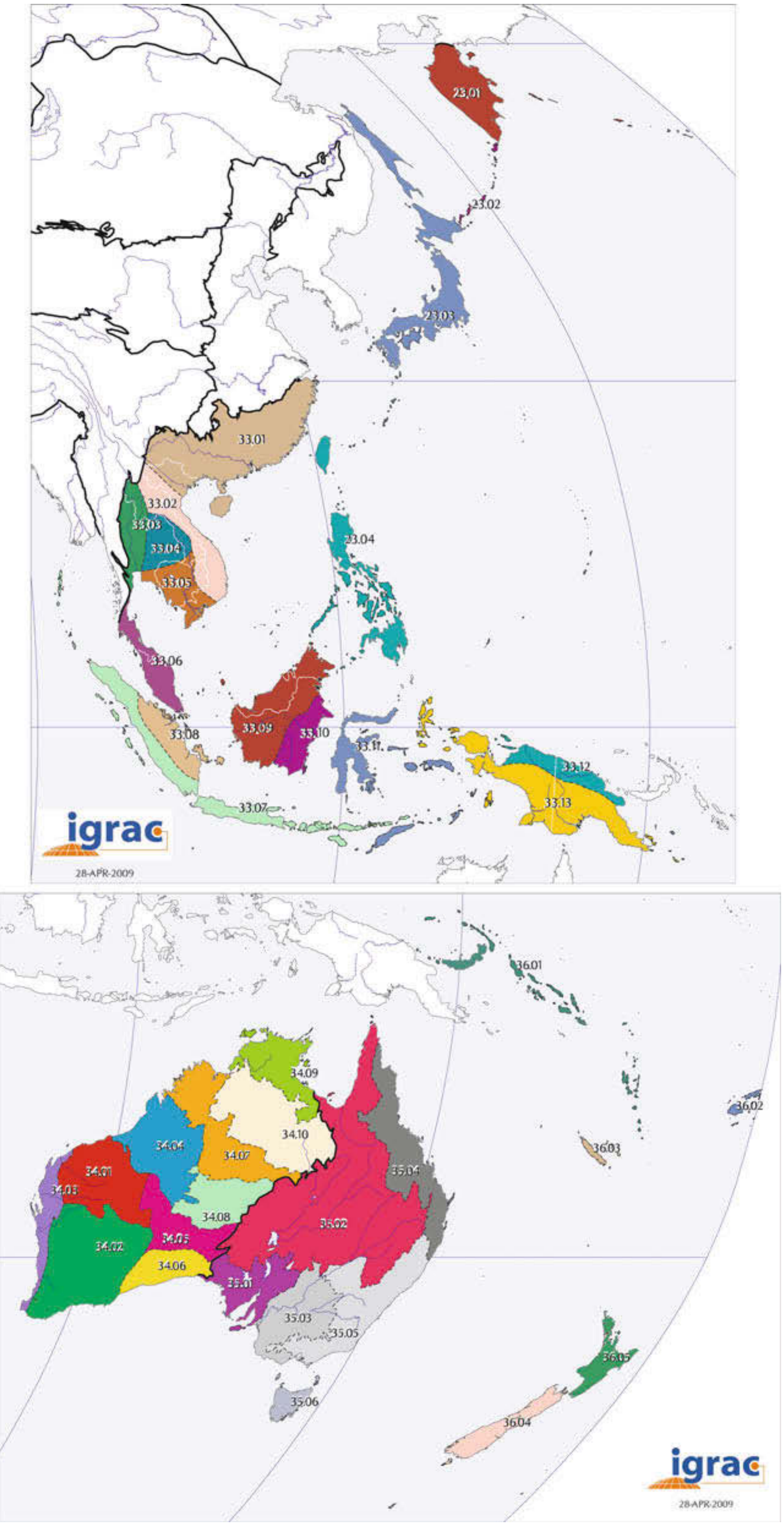


**Fig. 9** Groundwater provinces in Northern Asia and in Western & Southern Asia (reproduced with permission from IGRAC)

**Fig. 10** Groundwater provinces in Eastern Asia and in Ocania (reproduced with permission from IGRAC)



24.02 Mongol-Okhotsk Folded Region
24.03 Baikal-Patom Folded Region
24.04 Aldan Shield in East Siberia
24.05 Yinshah Da and Xia Hinggannling Uplift
24.06 Sikhote-Alin Folded Region
24.07 Korean Peninsula

### BASINS OF WEST AND CENTRAL ASIA

25.01 Central Kazakhstan Folded Region
25.02 Syr Darya Basin
25.03 Tian Shan Fold Belt
25.04 Junggar Basin
25.05 Tarim Basin
25.06 Altun Shan Fold Belt
25.07 Jinquan Minle Wuwei Basin
25.08 Ordos Basin
25.09 Shanxi Plateau
25.10 Taihang Shan Yanshan Fold Belt

### MOUNTAIN BELT OF WEST ASIA

26.01 Taurus Mountains
26.02 Anatolian Plateau
26.03 Caucasus
26.04 Central Iranian Basins
26.05 Elburz Mountains
26.06 Zagros Fold Belt and Trust Zone

### HIMALAYAS AND ASSOCIATED HIGHLANDS

27.01 Hindu Kush
27.02 Pamir High
27.03 Tibetan Plateau
27.04 Himalayas
27.05 Sichuan Basin
27.06 Tenasserim Shan

### PLAINS OF EASTERN CHINA

28.01 Manchurian Plain
28.02 North China Plain
28.03 Middle and Lower Chang Jiang River Basin

### INDO-GANGETIC-BRAHMAPUTRA PLAIN

29.01 Indus Basin
29.02 Ganges Basin
29.03 Brahmaputra Basin
29.04 Irrawaddy Basin

### NUBIAN AND ARABIAN SHIELDS

30.01 Red Sea Hills in Africa
30.02 Red Sea Coastal Plains
30.03 North Western Escarpment Mountains
30.04 Asir Mountains
30.05 Arabian Shield
30.06 Yemen Highlands

### LEVANT AND ARABIAN PLATFORM

31.01 Sinai
31.02 Euphrates-Tigris Basin
31.03 Al Hasa Plain in Saudi Arabia
31.04 Central Arch with Tuwayq Mountains
31.05 Rub Al Khali Basin
31.06 Marib and Shabwa Basins in Yemen
31.07 Masila-Jeza Basin
31.08 Mountains and Plains of Oman

### PENINSULAR INDIA AND SRI LANKA

32.01 Precambrian Basement in Southern and Eastern India
32.02 Precambrian Basement of Aravalli Range in Rajasthan
32.03 Precambrian Basement and Sediments of Sri Lanka
32.04 Deccan Trap
32.05 Coastal Sedimentary Areas

### PENINSULAS AND ISLANDS OF SOURH-EAST ASIA

33.01 South China Fold Belt
33.02 Truong Son Fold Belt
33.03 Thailand Basin
33.04 Khorat Platform
33.05 Tonle Sap-Phnom Penh Basin
33.06 Malay Peninsula
33.07 Sumatra-Java Magmatic Belt
33.08 Sumatra Basin
33.09 Sunda Platform
33.10 Barito-Kutei Basin
33.11 Sulawesi-Banda Magmatic Arch
33.12 Irian Basins
33.13 New Guinea Mobile Belt

### WEST AUSTRALIA

34.01 Pilbara Block
34.02 Yilgarn Basement Block
34.03 Carnarvon Basin
34.04 Canning Basin
34.05 Officer Basins
34.06 Eucla Basin
34.07 Kimberly Basement Block
34.08 Musgrave Basement Block
34.09 McArthur Basin
34.10 Wiso and Georgina Basins

### EAST AUSTRALIA

35.01 Gawler Ranges
35.02 Great Artesian Basin
35.03 Murray Basin
35.04 Great Dividing Range
35.05 Australian Alps
35.06 Tasmania Island

### ISLANDS OF THE PACIFIC

36.01 Bismarck-New Hebrides Volcanic Arc
36.02 Fiji Islands
36.03 Orogenic Belt of New Caledonia
36.04 Axial Tectonic Belt of New Zealand
36.05 Sedimentary Basins of New Zealand
36.06 Pacific Islands West of the American Continents

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# WHYMAP and the Groundwater Resources Map of the World 1:25,000,000

Andrea Richts, Wilhelm F. Struckmeier,
and Markus Zaepke

## Abstract

The Worldwide Hydrogeological Mapping and Assessment Programme (WHYMAP) was launched in 2002 by UNESCO as the lead agency within its International Hydrological Programme (IHP) and the UNESCO/IUGS International Geoscience Programme (IGCP), the Commission for the Geological Map of the World (CGMW), the International Association of Hydrogeologists (IAH), the International Atomic Energy Agency (IAEA) and the German Federal Institute for Geosciences and Natural Resources (BGR). WHYMAP aims at collecting, collating and visualising hydrogeological information at a global scale, to convey groundwater-related information in an appropriate way for global discussion on water issues and to give recognition to the invisible underground water resources within the UNESCO Programme on World Heritage. WHYMAP also brings together the huge efforts in hydrogeological mapping at regional, national and continental levels. Thus BGR, together with its partners, is gradually building up a geo-information system (WHYMAP-GIS) in which the groundwater data are managed and visualised. The WHYMAP steering committee cooperates closely with the International Groundwater Resources Assessment Centre (IGRAC) and the Global Runoff Data Centre (GRDC). Other regional centres, scientific organisations, universities and freelance experts in hydrogeology may also participate in the future. WHYMAP has produced two special editions of the global map at the scale of 1:50,000,000, i.e. one for the International Geological Congress and the CGMW meeting at Florence, Italy, August 2004, and a second focussing on Transboundary Aquifer Systems, issued for the 4th World Water Forum in Mexico City in March 2006. The latest is a 1:25,000,000 wall map of the Groundwater Resources of the World. It shows various characteristic groundwater environments in their areal extent: blue colour is used for large and rather uniform groundwater basins, green colour areas have complex hydrogeological structure, and brown colour symbolises regions with limited groundwater resources in local and shallow aquifers. In addition the groundwater recharge rates are shown by

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colour shades. Areas of heavy groundwater abstraction prone to over-exploitation and areas of groundwater mining are mapped, where known. Groundwater quality is also an important issue and areas of high groundwater salinity are highlighted. The global Groundwater Resources Map contains only selected information on groundwater. For reasons of clarity and readability, important complementary information has been deferred to a set of four insert maps at 1:120,000,000. These thematic maps show "mean annual precipitation", "river basins and mean annual river discharge", "population density" and "groundwater recharge per capita". Comparison between the main Groundwater Resources Map and these thematic maps should help understanding of the global picture of groundwater and surface water resources and provide insights into their pressures, in particular the priority use for drinking purposes. WHYMAP-GIS is updated regularly and map makers and hydrogeologists are invited to contribute to the programme.

**Keywords**

Groundwater • Global water agenda • Global overview • Hydrogeological map • Groundwater resources worldwide • UNESCO • IAH • BGR • WHYMAP

## Background and Motivation

During the past decades, water shortage problems at local, regional and even global levels have increased considerably. Rising demands from population and economic growth and food production call for larger and reliable quantities of water on the one hand, but declining resources due to pollution, over-pumping and climate and land use changes on the other hand reduce the per capita usable water resources. The needs of ecosystems and nature must be sustained in water resource management, too.

To meet these demands, policy makers often focus on surface water disregarding groundwater resources, which are found belowground, meaning "out of sight" and thus "out of mind". Or groundwater is treated as an unlimited, freely available common good, just used without considering renewable and non-renewable resources, or issues of water balance and pollution.

The use of groundwater presents in most cases a very economical, secure, reliable and sustainable solution to acute or persistent water shortage problems, particularly in semi-arid and arid regions of the world. Groundwater can supply millions of people safely with high-quality, clean drinking water – if the resources are properly and sustainably managed. Such sustainable use requires sufficient knowledge as well as careful planning, management and monitoring as part of the Integrated Water Resource Management (IWRM) concept.

## The Important Role of Groundwater

Groundwater is the largest accessible but often undervalued freshwater reservoir on earth. Among the world water resources 96.5% consists of salt water in the oceans and in salt lakes, 1% has to be considered saline groundwater not apt for use and only 2.5% remains for use as so-called freshwater. Almost 70% of these 2.5% is bound in glaciers, the polar caps and permafrost areas; only less than 1% can be found in rivers, lakes, wetlands, soil moisture and in the atmosphere, but about 30% is stored in aquifers as fresh groundwater. Neglecting the water masses stored in polar caps and in glaciers 96% of all freshwater is thus found in aquifers, namely 10.5 million km$^3$.

The world's aquifer resources are an important component in sustainable development. In the past three to five decades the withdrawal of water from aquifers has exponentially increased, reflecting humanity's increasing needs for food and industrial production. Global groundwater resource withdrawals are estimated at 600–800 km$^3$/year. Groundwater is the main drinking water source for more than a third of world's population. Agriculture and irrigation systems in many parts of the world depend on groundwater resources. Groundwater also has an ecological function, as it sustains spring discharges, river baseflow, lakes and wetlands and the aquatic habitats found in them. All in all almost 2 billion people on the planet entirely rely on a nearby aquifer for their daily water needs.

In principle there is enough freshwater to meet everyone's need, but the world's supply of freshwater is not evenly distributed. Many countries are already facing increasing scarcity of freshwater and by 2025, 1.8 billion people might be living in countries or regions with pressing water scarcity problems. In addition climate change will certainly have an impact on water resources and their management. As temperature rises, rainfall patterns are expected to change, increasing the risk of floods, drought and other water-related disasters in many areas.

There is still great lack of understanding the basics of underground flow and the need for sustainable use of the groundwater resource. Unfortunately information on these hidden resources is still weak in many places, resulting in weak investments in groundwater schemes founded on inadequate aquifer information in terms of quantitative data, reliable models and poor monitoring.

Furthermore the extent of aquifers does not follow political borders and many of them are transboundary. Thus besides the necessary national groundwater management, regional strategies are required and bilateral or multilateral agreements need to be concluded for aquifer management. More than half of the international river basins and transboundary aquifer systems do not have any type of cooperative management framework in place.

Around the turn of the century, UNESCO, the International Association of Hydrogeologists (IAH) and a number of international partners launched a project named "Worldwide Hydrogeological Mapping and Assessment Programme (WHYMAP)". It aims at collecting, collating and visualising hydrogeological information at the global scale, to convey groundwater-related information in an appropriate way for global discussion on water issues and to raise awareness for the invisible underground water resources by compiling data on groundwater from national, regional and global sources. The generated products provide information on quantity, quality and vulnerability of the groundwater resources on earth. By visualising the hidden resources through global maps and web map applications WHYMAP helps communicating groundwater-related issues to water experts as well as decision makers and the general public. WHYMAP is also well recognised as an important contribution for the political discussions on global water issues.

## The WHYMAP

### Project History and Design

In order to contribute to the worldwide efforts to better study and manage aquifer resources, the joint map commission of both IAH (International Association of Hydrogeologists) and CGMW (Commission for the Geological Map of the World) submitted a proposal to UNESCO. This was launched in 1999 as the Worldwide Hydrogeological Mapping and Assessment Programme (WHYMAP) and included in the International Hydrological Programme (IHP) of UNESCO.

WHYMAP was supposed to bring together the huge efforts in hydrogeological mapping at regional, national and continental levels permitting an overview and comparison of the major aquifer systems of the world including their groundwater resources and recharge.

Several agencies joined UNESCO and CGMW and provided their specific contribution to WHYMAP. A consortium was established in 2002, consisting of the UNESCO-IHP, the UNESCO/IUGS International Geoscience Programme (IGCP), CGMW, IAH, the International Atomic Energy Agency (IAEA) and the German Federal Institute for Geosciences and Natural Resources (BGR). The consortium is responsible for the general thematic outline and the management of the programme. BGR as the executing unit provides important resources in terms of manpower, mapping capabilities and data. All partners are committed to supply relevant scientific input and to care for a co-ordinated action.

The participation of regional experts focussing on the relevant regional groundwater knowledge and information is considered crucial for WHYMAP. A steering committee of eminent international experts was established under the supervision of the consortium in 2003. The steering committee is supported by the continental vice presidents of the IAH and CGMW, the UNESCO regional offices and the national committees of the UNESCO-IHP. A number of meetings in Koblenz and Paris ensured a scientific and technical sound approach and extensive review and quality control of the compiled data.

Close cooperation with the International Groundwater Resources Assessment Centre (IGRAC) is assured through UNESCO, and the WHYMAP data are shared with IGRAC. Furthermore, the Global Runoff Data Centre (GRDC) has become part of the network providing valuable global and regional data sets of surface water systems, and the research groups of the Universities of Frankfurt and Kassel who developed the WaterGAP model provided groundwater recharge data that were integrated into the WHYMAP world maps. Other regional centres, scientific organisations, universities and freelance experts in hydrogeology have also participated in WHYMAP occasionally. The structure of the WHYMAP network is shown in Fig. 1.

## The WHYMAP Geo-information System (WHYMAP-GIS)

In order to allow the integration of large amounts of data of very different origin and to ensure flexibility and reproducibility of the products, one main focus of the WHYMAP was the establishment of a geo-information system (GIS) in which global groundwater maps and related vector and raster data are stored and processed. The design and creation of the GIS had to meet different requirements: the data structure had to prove useful for both the handling and processing of the digital data as well as for the representation of cartographic aspects for the output of high-quality thematic maps.

In its final form the WHYMAP-GIS is supposed to contain a number of thematic layers, e.g.

- structural hydrogeological units
  - sedimentary basins
  - coastal aquifers
  - complex hydrogeological regions with important aquifers

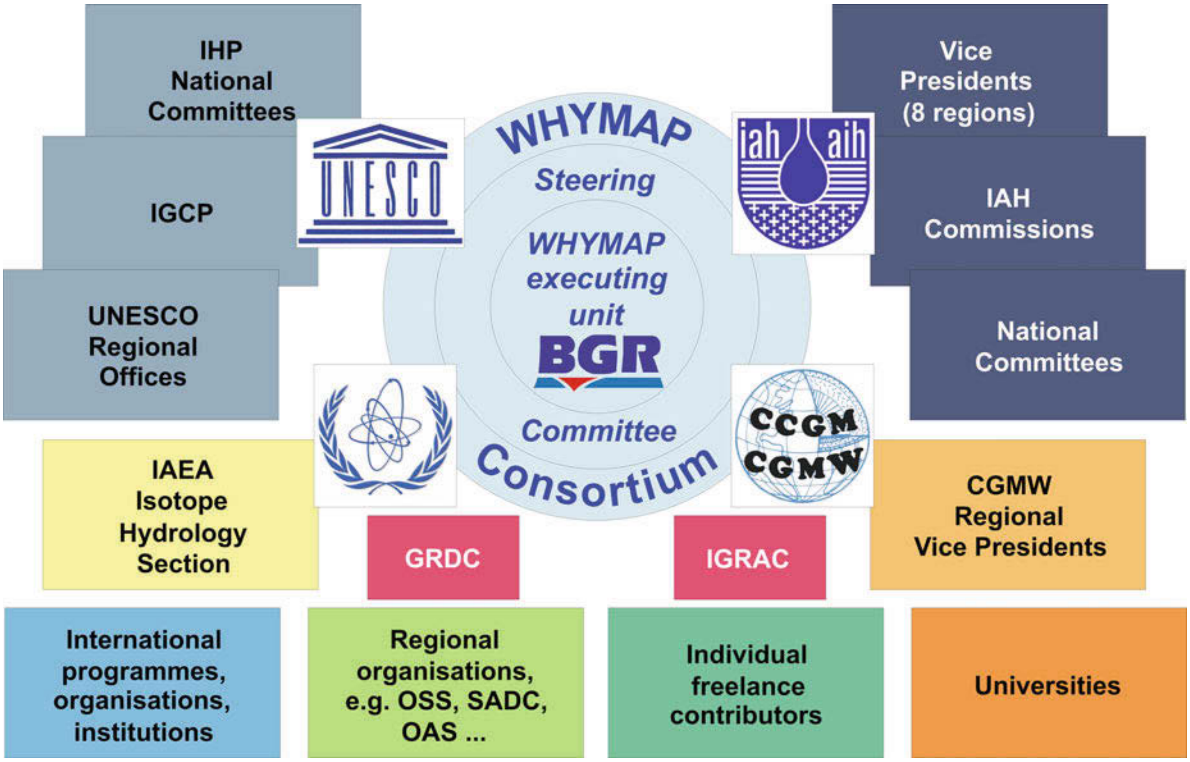


**Fig. 1** The WHYMAP network

  - karst aquifers
  - local and shallow aquifers
- transboundary aquifer systems
- aquifer properties
- groundwater potential
- storage volumes
- accessibility and exploitability of groundwater resources
- groundwater recharge (renewable/non-renewable)
- groundwater runoff, discharge, climatic dependence
- groundwater exploitation (sustainable/mining)
- depth/thickness of aquifers
- hydrodynamic conditions (groundwater divides/flow directions/confined – artesian conditions)
- groundwater vulnerability
- interaction with surface water bodies
- land subsidence
- permafrost
- geothermalism
- hydrochemistry
- stress situations of large groundwater bodies
- "at-risk" areas

All WHYMAP products (see below) are based on this WHYMAP-GIS and parts of the system are open to the public via an Internet-based map application or web map service (WMS).

## Products

From the WHYMAP-GIS database a variety of high-quality thematic map products at different scales and complexity have been derived so far.

The first overview sketch map was produced in 2003, presented at the 3rd World Water Forum in Japan and published in the first World Water Development Report (WWDR). In 2004, a first global groundwater resources map at a scale of 1:50,000,000 was released at the International Geological Congress in Florence to raise awareness for the programme and generate additional input to WHYMAP. Another global map focusing on transboundary aquifer systems followed at the 4th World Water Forum in Mexico City in 2006 (BGR/UNESCO 2006).

The most recent publication is the Groundwater Resources Map of the World at the scale of 1:25,000,000, published 2008 as a contribution to the International Year of Planet Earth (IYPE) (BGR/UNESCO 2008). It summarises all data compiled so far and shows the characteristic groundwater environments in their areal extent (see Chapter 3).

Various small-scale maps showing the global groundwater situation and other related issues are consistently developed as kind of by-products for use as figures in reports and publications (see Fig. 2). They are often provided to satisfy individual requests and requirements of different users and already found their way into several atlas projects and scientific publications and are used for educational purposes or provided input for further global studies on water-related issues.

WHYMAP also serves as an entry gate for more detailed, national and regional hydrogeological map information all over the world. An Internet-based map application has been developed which combines the presentation of WHYMAP data with an information system on national, regional and continental hydrogeological maps. This "Worldwide Hydrogeological Mapping Information System (WHYMIS)" was integrated into the application because of two essential functions. On the one hand, it offers users searching for more detailed hydrogeological information a direct link to national web sites as well as existing printed maps, together with a set of metadata; it also serves as an archive function, in particular capturing maps of less developed countries that are all too often lost or not available to interested map users. The WHYMAP data are also provided as web map service and Google Earth layer.

All WHYMAP products and services are accessible via the project web site www.whymap.org.

## The Global Groundwater Resources Map

### The Process of Developing a GIS-Based Global Groundwater Map

The compilation and printing of appealing global groundwater maps is closely interrelated with the gradual installation of the WHYMAP geo-information system (GIS) for the storage, processing and visualisation of groundwater relevant information and other data on a global scale. The process of (digital) map compilation can be summarised as follows:

- select a topographic base map and projection
- develop the legend and representation concept
- design and create the GIS structure
- review information from existing data sources
- compile continental drafts at scale 1:10,000,000

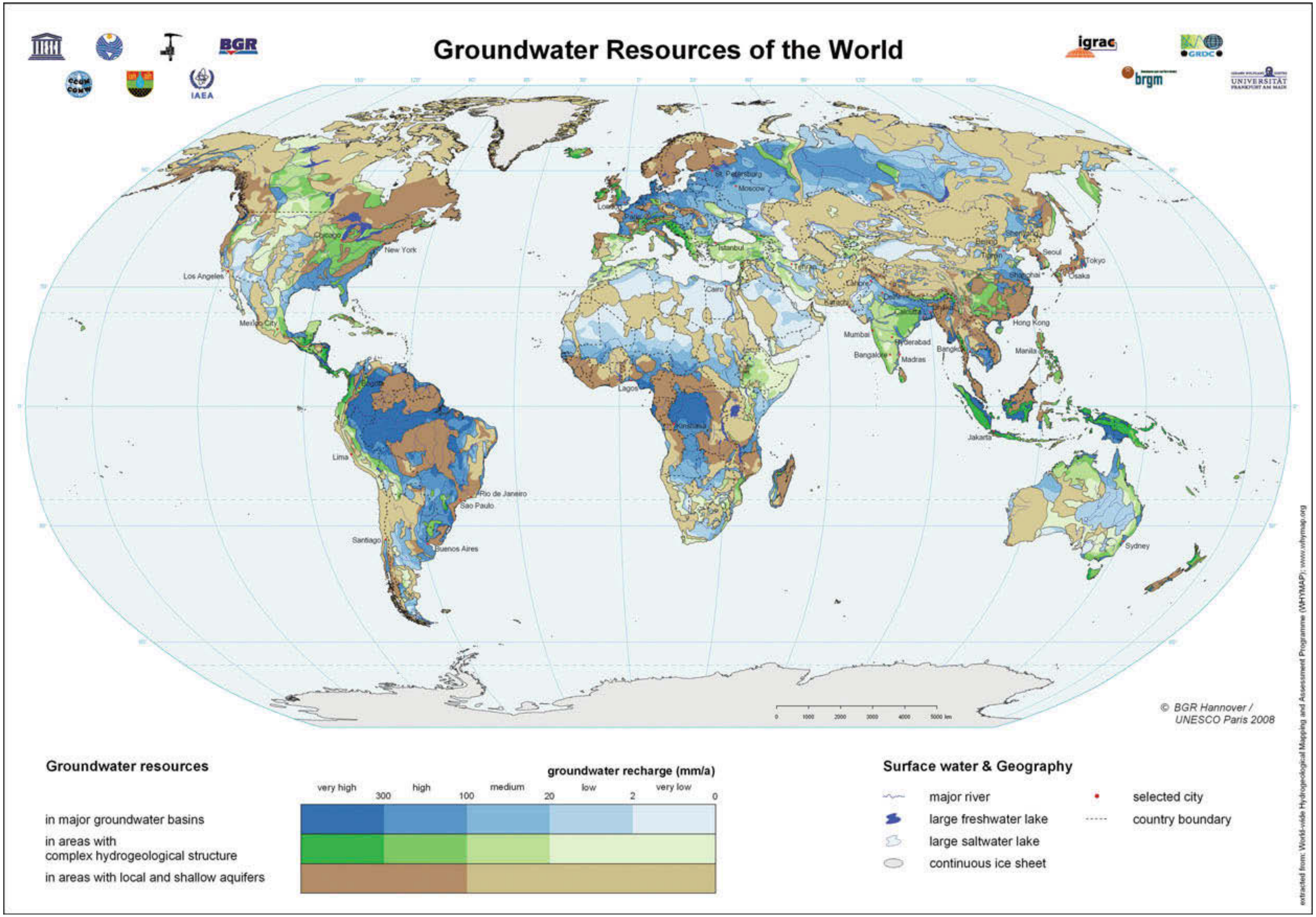


**Fig. 2** Simplified groundwater resources map of the world used as text figure

- digitise continental drafts and add attributes in GIS
- prepare first drafts of the global groundwater map and other thematic layers
- discuss and improve drafts with members of WHYMAP steering committee, IAH vice presidents, CGMW vice presidents and IHP regional offices
- complete and optimise WHYMAP-GIS including cartographic layout
- compile and print the final global groundwater resources map at scale 1:25,000,000

The selection of the appropriate data sources was a very sensitive aspect in the beginning. BGR started to evaluate existing national, regional and continental maps at small to very small scales from 1:1,000,000 to approximately 1:15,000,000, existing databases and statistical material concerning groundwater, surface water, precipitation and population density (as an expression of the stress on the fresh water resources), and the data collection was greatly fostered by the members of the steering committee. In many cases, however, the statistics relate to countries as an entity rather than to the actual geographic distribution within the country. Caution therefore is recommended in cases of vast territories or extremely variable hydrogeological conditions.

Although the input data originate from national files and data banks, even if stored in regional or international data centres, a world map should show a coherent, inter- or supranational picture. There is no doubt that the quality of data differs, despite efforts to impose an international standard for the collection and treatment of data, since the information depicted on the map is just as good as the data delivered.

In addition to making use of the data archives of national institutions and international organisations primarily the following existing maps at global, continental and regional scales have finally been thoroughly studied:

- Geological Map of the World 1:25,000,000 (compiled by UNESCO, CGMW, BRGM in 1990)
- Maps of the World Environment During the Last Two Climatic Extremes 1:25,000,000 (1999)
- World Map of Hydrogeological Conditions and Groundwater Flow 1:10,000,000 (compiled by the Water Problems Institute, Russian Academy of Sciences under UNESCO supervision in 1999)
- Maps of the WaterGAP Model of the Universities of Kassel and Frankfurt (2003, 2006)
- A number of regional or continental small-scale maps:
  - Hydrogeological Map of Australia 1:5,000,000 (1987)
  - Hydrogeological Map of the Arab Region and Adjacent Areas 1:5,000,000 2 sheets (1988)
  - Hydrogeology of North America 2 maps 1:13,333,333 (1988/89)
  - Ground Water in North and West Africa, 2 maps 1:20,000,000 (1988)
  - Middle East Hydrogeology 1:8,000,000 (1990)
  - International Hydrogeological Map of Africa 1:5,000,000 6 sheets (1992)
  - International Hydrogeological Map of South America (Mapa hidrogeologico de America del Sur) 1:5,000,000 2 sheets (1996)
  - Hydrogeology of the Great Artesian Basin 1:2,500,000 (1997)
  - Hydrogeological Map of Asia 1:8,000,000 6 sheets (1997)
  - The National Atlas of the United States of America, Principal Aquifers 1:5,000,000 (1998)
  - International Hydrogeological Map of Europe 1:1,500,000, 28 sheets (since 1970 under production)

The generation of the global maps started with the preparation of continental drafts at the working scale of 1:10,000,000 (see Fig. 3) based on existing hydrogeological maps and data of continents, regions and countries. The challenge here was to make all individual groundwater data and information compatible and comparable to obtain a consistent picture of the hydrogeological situation on the globe with comparable representation of all continents. First, the scale of these maps differs significantly and usually they provide much more details that can be shown on the world map, meaning that hydrogeological conditions had to be simplified in order to avoid an overloading with details. The second reason for not simply putting together the regional maps was that each of these maps differs in philosophy, approach and hydrogeological interpretation. Another crucial point was the handling of often unknown projection information of the available maps serving as data sources and thus the transformation into the Robinson projection which has been chosen for the global maps.

As a consequence all maps had to be carefully reviewed and often redrawn in order to arrive at a common approach valid for all continents. The final

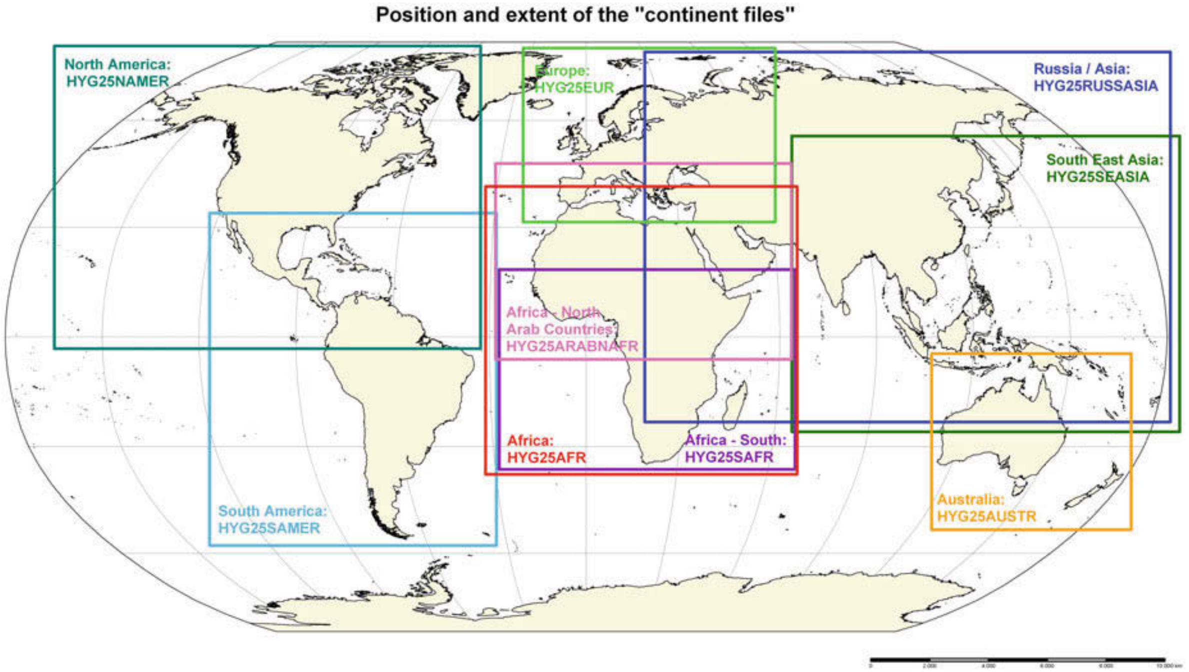


**Fig. 3** Subdivision of the global map into continental work sheets at the scale of 1:10,000,000

revision and completion of the continental drafts was performed by the members of the steering committee as well as other hydrogeological mapping experts from all parts of the world, making use of their regional knowledge. Finally, a new consistent global groundwater map was compiled by adjusting and merging the continental drafts.

Step by step, different thematic layers are prepared for the global groundwater map, partly under the supervision of one of the partners. For instance, the information on groundwater recharge is developed under the auspices of IAEA; the layer on transboundary aquifer systems is mainly realised by IGRAC and the Internationally Shared Aquifer Resources Management (ISARM) group of UNESCO (Puri, Aureli 2009). Different IAH commissions are working on global maps of karst aquifers, groundwater vulnerability, coastal aquifers and the hydrogeology of hard rocks.

## Description of the World Map of Groundwater Resources and Its Legend

The Groundwater Resources Map of the World at the scale of 1:25,000,000 published in 2008 is a major result of WHYMAP and lumps the related data known or published so far. It shows various characteristic groundwater environments in their areal extent: blue colour is used for large and rather uniform groundwater basins (aquifers and aquifer systems usually in large sedimentary basins that may offer good conditions for groundwater exploitation), green colour areas have complex hydrogeological structure (with highly productive aquifers in heterogeneous folded or faulted regions in close vicinity to non-aquifers) and brown colour symbolises regions with limited groundwater resources in local and shallow aquifers.

Within the three main hydrogeological units up to five different categories are defined according to their potential recharge rates from over 300 mm to less than 2 mm/year ranging from dark blue, green and brown colours representing areas with very high recharge rates to light blue, green and brown colours outlining regions with very low recharge potential. The latter category is vulnerable to groundwater mining. Groundwater recharge rates refer to the standard hydrologic period 1961–1990 and are derived from simulations with the global hydrological model WaterGAP, version 2.1f, provided by the University of Frankfurt (Döll, Fiedler 2008).

A number of important groundwater features usually localised to small areas or points are shown by point symbols on the main map. This refers mainly to arid regions where groundwater discharges on ground level (e.g. endorheic basins or chotts and sebkhas). Such discharge points are usually related to deeper aquifers in which groundwater is under pressure and rises up to the surface. Such places have formed famous water points in historic times and may be sustaining valuable aquatic ecosystems.

Many wetlands that are likely to be sustained by groundwater are also shown on the map. Most of them have been selected from the International Union for Conservation of Nature (IUCN) database on sites covered by the RAMSAR convention. However, it is evident that the density of sites in many countries reflects the status of environmental awareness of governments and administrations rather than the true existence of wetland sites that are relevant for biodiversity or may be an indicator for the status of the natural environment.

Important sites of groundwater abstraction have also been shown on the map, where known. This feature highlights places of heavy groundwater pumping usually related with a drawdown of groundwater levels, or even groundwater mining in places where there is almost no present-day recharge.

Orange hatching has been applied in areas where the salinity of the groundwater regionally exceeds 3–5 g/l. In these places the groundwater is generally not suitable for human consumption, but some livestock may find it drinkable.

Parts of the northern latitudes close to the Arctic are affected by permafrost. Here even the groundwater is generally frozen and unusable for water supply. The boundary of permafrost therefore has been indicated by a dark green line on the map.

The surface water features should provide a general idea about the relationship between groundwater, lakes and large rivers. They have been provided by Global Runoff Data Centre (GRDC) in close cooperation with BGR on the basis of long-term average runoff data. Accumulations of inland ice and large glaciers have been shown by grey colour wash. About two-thirds of the global freshwater resources are represented by these ice sheets; however, they are generally confined to remote and unpopulated areas and are thus of less importance for water supply.

The topographic features shown on the map answer the need for orientation and geographic reference. Major population centres usually represent points of peak water demand. In the first instance, the cities with a population exceeding 3 million inhabitants were shown, but a number of smaller population centres have been added for the sake of geographic reference. The political boundaries, which are taken from the global data sets of United Nations Cartographic Section, highlight that most of the groundwater areas worldwide cross political borders, forming shared transboundary aquifers.

The legend (see Fig. 4) follows those applied elsewhere in regional and continental hydrogeological maps and it largely adopts the international standard legend for hydrogeological maps published by IAH in 1995 (Struckmeier, Margat 1995).

## Inset Maps

The Groundwater Resources Map of the World provides only selected information related to groundwater. Other complementary information is necessary to be able to understand the global picture of groundwater and surface water resources and provide insight into their pressures. Thus WHYMAP strives to compare and combine its own results with other thematic maps, e.g. on precipitation, surface water, recharge or population density.

One of these shows the main input to all water systems on earth, namely the rainfall pattern. This data was provided by the Global Precipitation and Climate Center of the World Meteorological Organisation (WMO) (GPCC in Offenbach/Germany). It has been computed by using data from the international standard hydrological period 1961–1990.

Similar data were used as an entry to the global WaterGAP model developed at the Universities of Kassel and Frankfurt in Germany. From this model, a global map of groundwater recharge per capita has been derived. The map shows rather large variations from country to country. In several large countries with federal structures, e.g. Australia, Brazil, China, India, Mexico, Russia and the United States, the data have been related to the individual states.

A map of “River Basins and Mean Annual River Discharge” has been compiled by the GRDC in Koblenz/Germany in cooperation with the University of Frankfurt and WHYMAP. It shows the major surface water catchment basins together with the corresponding river courses and lakes, which have been

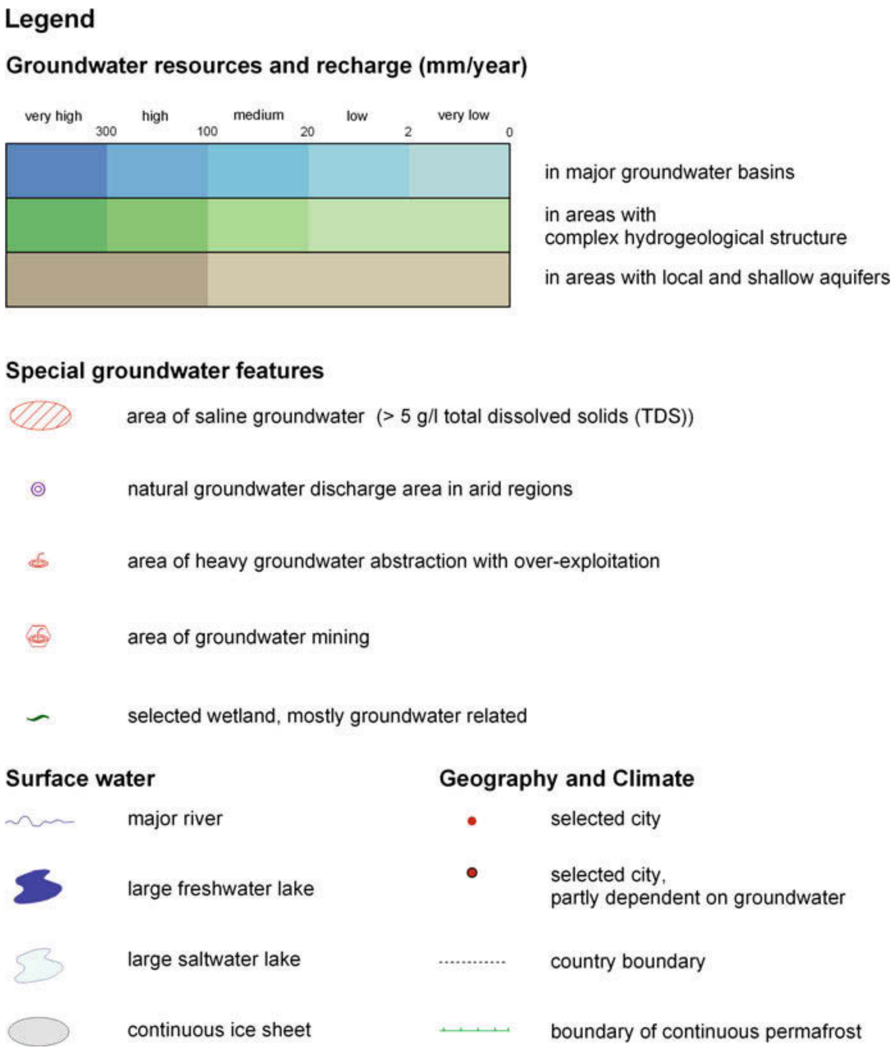


**Fig. 4** Legend of the groundwater resources map of the world, 2008

classified according to their mean annual discharge (see Fig. 5).

Another theme is population density, as derived from the gridded population of the world, version 3. Although the per capita water demand varies considerably between less than 20 l per person and day in developing countries to more than 500 in certain wealthy arid countries, the map may allow a rough grasp on the pressures on the water resources including groundwater owing to the number of people living on earth.

The maps also show the various ways of representation of geographic data, from true geographical distribution (polygons related to the earth's surface) via raster cells (pixels) to information for political units, mainly countries or states.

They are included as inset maps on the published paper map sheets of the Groundwater Resources Map of the World.

## Conclusions from WHYMAP

Some general conclusions can be drawn from analyses of the global groundwater maps and data:

*Groundwater is found almost everywhere, but varies strongly regarding quantity, quality and recharge*. Therefore, sustainable use of groundwater resources,

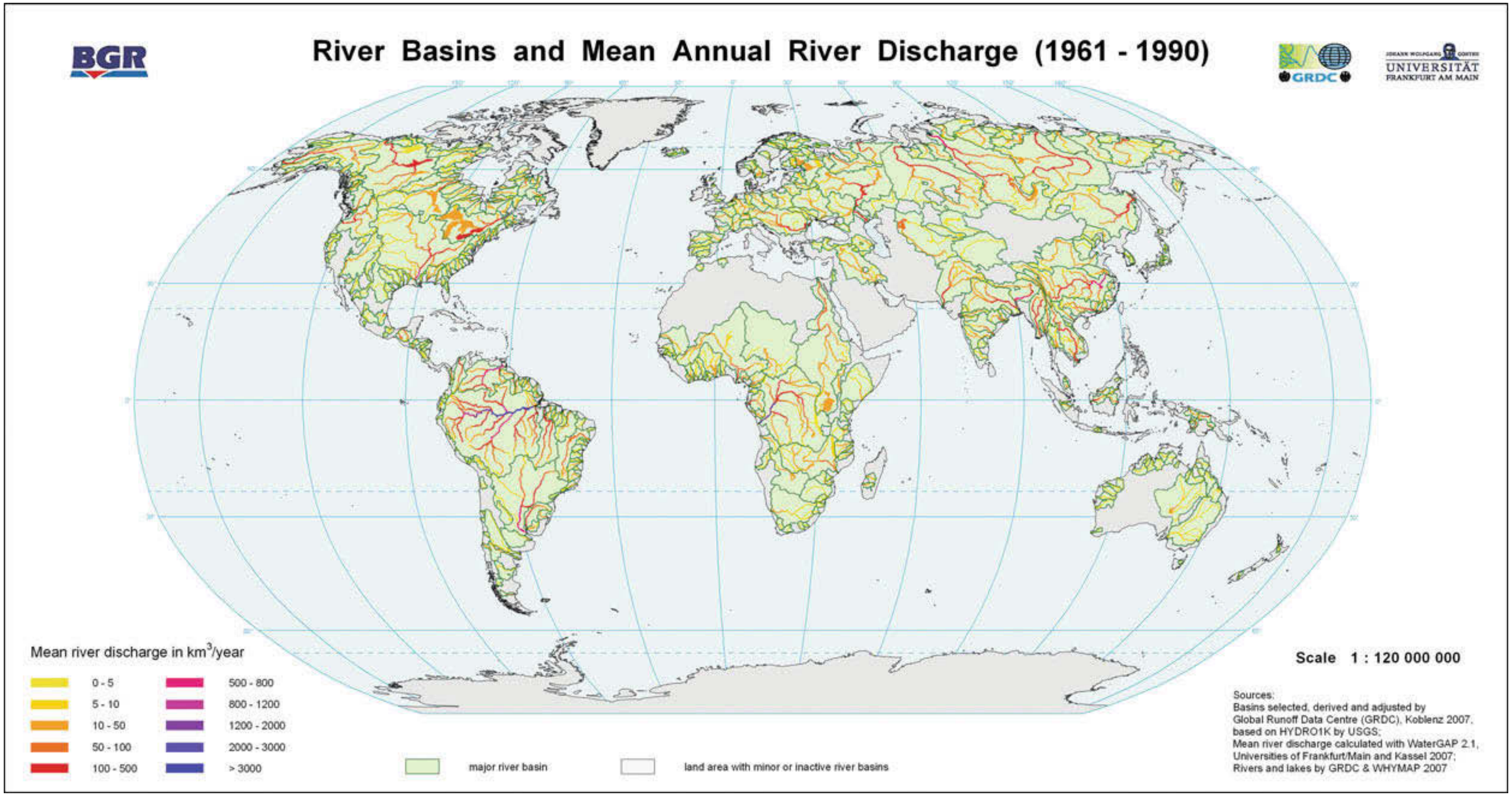


**Fig. 5** River basins and mean annual river discharge

**Table 1** Distribution of the various hydrogeological types by continent

| | Major groundwater basins | | Complex hydrogeological structures | | Local and shallow aquifers | |
|---|---|---|---|---|---|---|
| | (million km$^2$) | (%) | (million km$^2$) | (%) | (million km$^2$) | (%) |
| **Africa** | 13.48 | 44.9 | 3.31 | 11.0 | 13.22 | 44.1 |
| **Asia** | 14.54 | 32.0 | 7.84 | 17.3 | 22.98 | 50.7 |
| **Australia, New Zealand** | 2.60 | 32.5 | 2.90 | 36.3 | 2.49 | 31.1 |
| **Europe** | 5.15 | 53.0 | 1.82 | 18.8 | 2.74 | 28.2 |
| **Central/South America** | 8.35 | 45.0 | 2.02 | 10.9 | 8.18 | 44.1 |
| **North America** | 3.21 | 15.0 | 5.75 | 26.9 | 12.40 | 58.1 |
| **World (excl. Antarctica)** | 47.32 | 35.6 | 23.64 | 17.8 | 62.02 | 46.6 |

particularly for drinking water supply or irrigated food production, requires a thorough assessment.

The *areal distribution of the various hydrogeological types* mapped on the groundwater resources map shows that, as a global average, half of the land surface (47%) of the continents (excluding the Antarctic) is made up of local and shallow aquifers with minor occurrences of groundwater (in these areas groundwater is limited to the alteration zone of the bedrock that may also contain local productive aquifers). Approximately 35% of the land subsurface host relatively homogeneous aquifers usually in large sedimentary basins that may offer good conditions for groundwater exploitation and 18% of the land subsurface comprise aquifers in a geologically complex setting with highly productive aquifers in heterogeneous folded or faulted regions in close vicinity to non-aquifers. This subdivision varies from continent to continent, as outlined in the following table (Table 1).

*Groundwater is heavily used* all over the world, but in certain areas the quantities of groundwater pumped is much higher than the annual recharge. This leads to continuously falling groundwater levels and is considered unsustainable, if no action is taken to increase the recharge or stop the trend of falling water levels. In many arid regions of the world, where there is no or very little natural recharge, fossil groundwater resources may be used to sustain life. It must be clear that this fossil groundwater mining can only be justified by particular development needs and must be carefully planned and monitored. Their exploitation for agriculture should be reduced in order to stretch out the life span of the limited resources to future generations. In the groundwater resources map, the known centres of major groundwater abstraction with over-exploitation and groundwater mining have been included. This information has also been extracted in a small sketch map (see Fig. 6).

In contrast, the point features related to *groundwater discharge in arid regions and the wetlands supposedly related to groundwater* provide an indication of the important environmental significance of groundwater. While the groundwater discharge points are relatively well documented even in historic literature, the number of groundwater-related wetlands is likely to increase considerably, if the environmental community would embark on a true global inventory of such sites (and not only capture the sites declared under the RAMSAR convention). So the number of groundwater-related wetlands yet to be identified may be surprisingly high.

Most of the large groundwater units form *shared transboundary aquifers*. They require an integrated management and close cooperation of all participating countries to guarantee a sustainable use. The ISARM initiative of UNESCO and IAH is working on this issue in cooperation with WHYMAP and IGRAC. The "Atlas of Transboundary Aquifers" published by ISARM/UNESCO-IHP in 2009 has identified 275 transboundary aquifers so far and the number is expected to grow due to more detailed investigations that will be conducted in the future.

In the arid and semi-arid regions of the world the location, *size and delineation of the surface river basins and the underlying aquifer system rarely coincide*. One of the most prominent examples is the African continent, mainly Northern Africa, where river basins and groundwater units are significantly different (see Fig. 7). Integrated water resources management areas must thus be reasonably selected and must not solely be based on river basins to avoid misconceptions

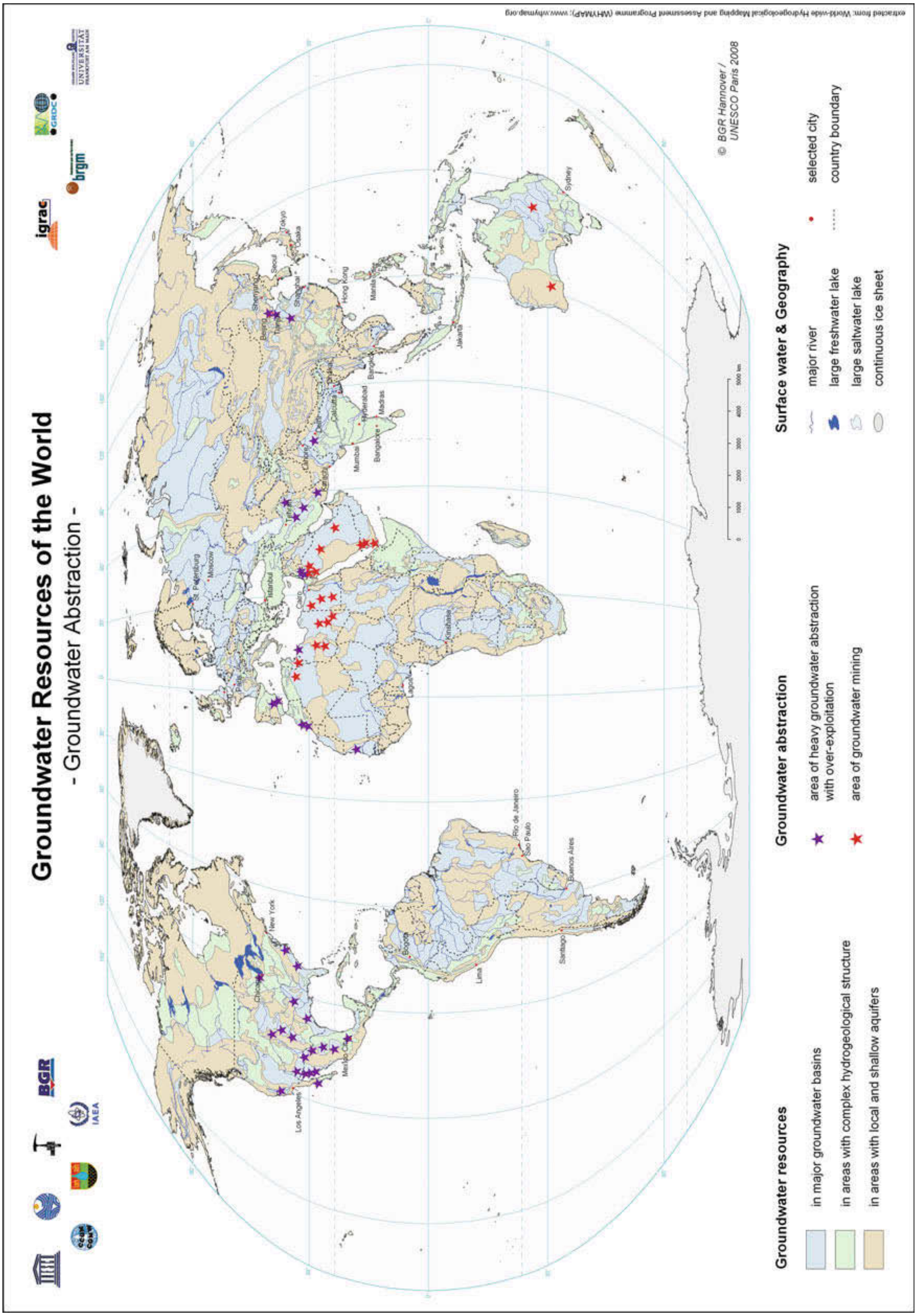
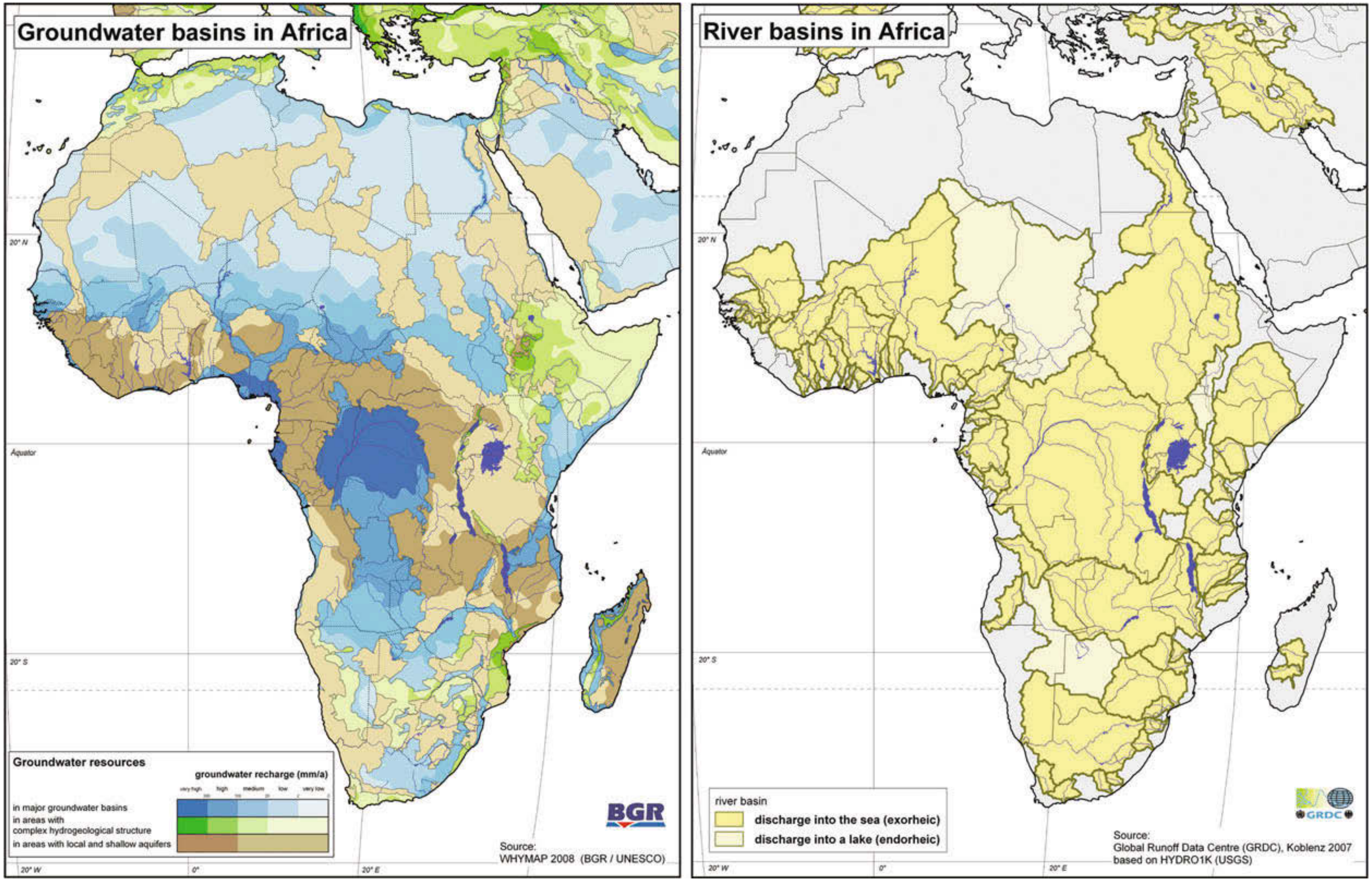


**Fig. 6** Groundwater over-exploitation and mining



Source:
WHYMAP 2008 (BGR / UNESCO)

Source:
Global Runoff Data Centre (GRDC), Koblenz 2007
based on HYDRO1K (USGS)

**Fig. 7** Comparison of groundwater basins (extracted from WHYMAP) and river basins (by GRDC) in Africa for water management. Particularly in low rainfall areas where surface water resources are random and unreliable, groundwater features must be considered adequately.

## Outlook

The publication of the educational wall map at a scale of 1:25,000,000 in 2008 was one major objective of the WHYMAP. The development and maintenance of the WHYMAP-GIS will continue to improve the availability of groundwater-related information to support international water management activities and raise the awareness among politicians and the general public of groundwater as an important natural resource. Therefore, a number of additional, relevant layers will be gradually captured for the WHYMAP-GIS.

With the WHYMAP achievements, the essential groundwater resources will receive an improved profile on the global water agenda. This is particularly necessary, because groundwater is a hidden, invisible asset for mankind and nature, and more awareness needs to be created in order to manage it properly and protect it from degradation.

The small scale does not allow recognising detailed individual issues and one of the conclusions might be to embark on maps at much larger scales, particularly for zones at risk and for disputed internationally shared resources. However, such more applied maps will benefit from the experience which can be drawn from the WHYMAP enterprise and they may be easily linked into WHYMIS.

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# Overview of a Multifaceted Research Program in Bénin, West Africa: An International Year of Planet Earth Groundwater Project

Stephen E. Silliman, Moussa Boukari,
Landry Lougbegnon, and Felix Azonsi

**Abstract**

Long-term collaboration (more than 10 years of continuing projects) among four partners has evolved from a local effort to drill groundwater wells into a multifaceted program of research and applications related to groundwater development, characterization, and protection in Bénin, West Africa. The project partners include the following: (i) a national university in Bénin, (ii) a private university in the United States, (iii) a government agency charged with development of water resources in Bénin, and (iv) a Bénin NGO focusing on the social and practical aspects of development. Continuing efforts of this partnership are being pursued under the badge of the UNESCO International Year of Planet Earth. Prior efforts associated with this project include the following: (i) modeling of a major aquifer in southern Bénin, (ii) development and statistical analysis of a regional database on element concentrations in groundwater, (iii) development of a water quality monitoring program based on collaboration with a local (rural) population, (iv) educational collaboration, and (v) drilling of groundwater wells for rural villages. Vision for the future of the project includes continuing improvement of the model for groundwater flow/transport in the southern aquifer system (including both numerical and field characterization efforts), transfer of a water quality monitoring project from the universities to the government agency, development of wellhead management/protection strategies for rural Bénin, expanded collaboration in the education efforts, and continuing research efforts focused on method development and capacity building in both Bénin and the United States.

**Keywords**

Groundwater • Wells • Water quality • Modeling • Student collaboration • Nitrates • Salt water intrusion • Africa • Benin

## Introduction

Four partner agencies have, over the past decade, explored a number of questions related to groundwater resources in Bénin, West Africa. This collaboration

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among the Université d'Abomey-Calavi (UAC – Bénin), the University of Notre Dame (UND – United States), Direction Generale de l'Eau (DGEau – a government agency in Bénin), and Centre Afrika Obota (CAO – an NGO in Bénin) was initially focused on two issues: (i) use of a small, rotary drill rig for drilling shallow wells in southern Bénin and (ii) the potential for educational interactions among the two universities. Development of mutual trust and common interests among these partners led to expanding this collaboration to include, in the realm of groundwater, research on groundwater quality in rural Bénin (Crane et al., 2009; Silliman et al., 2007, 2008), student collaborations among the two universities (Silliman, 2003, 2007; Silliman et al., 2005), modeling efforts on coastal Bénin (Boukari et al., 2008), and research on local populations as key players in developing long-term water quality databases for rural regions (Crane et al., 2009; Crane and Silliman, 2009). This chapter provides an overview of the historical efforts of this partnership, as well as vision of the future.

## Brief Chronological Program History

Program activities and dates are summarized in Table 1. The partnership was initiated in 1998 when a representative from UND traveled to Bénin to discuss the potential for a drilling project (with CAO and DGEau as primary partners) and explore options for collaboration between UND and UAC. Initiated by an invitation to UND from CAO, this trip involved separate efforts: (i) to visit a number of potential well drill sites and (ii) to initiate conversation with UAC.

The initial planning resulted, in the year 2000, in a small drill rig being used to train a local population (Hombo, Bénin) in basic drilling techniques: this effort, performed in collaboration with a US NGO (Lifewater International, San Luis Obispo, CA), resulted in the drilling of a single well equipped with a hand pump. Significantly, success in the drilling of the well required collaboration among each of the partners with UAC providing local expertise in hydrogeology as well as students to assist in the effort, CAO leading communication with the population in the village and oversight of the training efforts, DGEau providing necessary permits to drill and oversight of pump installation (with local participation in the drilling process replacing the customary cost share expected from the local community), and UND providing expertise (in collaboration with Lifewater International) in hydrology and the drilling/development of the well. This early need for collaboration among groups established an important foundation of trust and respect for the future project efforts.

Regional characterization of groundwater element chemistry was also initiated in 2000 via collaboration predominantly between UAC and UND. Supported by a planning grant from the US National Science Foundation, this effort involved collection of groundwater samples from several regions of central and northern Bénin, as delineated by those regions deriving water from fractured igneous and metamorphic rocks.

The first inclusion of US students within the partnership occurred in 2002 through a field characterization campaign to extend the previous groundwater sampling. Based on an NSF REU (Research Experience for Undergraduates) grant, three groups of US students participated in groundwater sampling as part of a summer research program (summers of 2002/3/4).

Two significant advances in the partnership were introduced in 2003. First, based on historical nitrate

**Table 1** Overview of the various historical components of the Bénin program showing years of activity in each aspect of the program

| | Well drilling | Elemental chemistry | Educational initiatives | Nitrate program | Numerical modeling | Community monitoring |
|---|---|---|---|---|---|---|
| 1998 | X | | | | | |
| 2000 | X | X | | | | |
| 2002 | | X | X | | | |
| 2003 | | X | X | X | | |
| 2004 | | X | X | X | | X |
| 2005 | | X | X | X | | X |
| 2006 | | | X | X | X | X |
| 2007 | X | | X | X | X | X |
| 2008 | X | | X | X | X | X |

data collected by DGEau, the partnership focused the field sampling campaign during the summer of 2003 on nitrate contamination in the Colline region of Bénin. Second, based on the developing relationship between UND and UAC, a short course was offered by UND at UAC to UAC students. This effort involved introduction of the students to both the MATLAB© programming environment (http://www.mathworks.com/) and basic concepts in geostatistics. This course has since been followed by additional offerings at UAC on geostatistics (repeat), programming, groundwater modeling, and field characterization methods, with one of the courses offered to a combined UAC/UND student body. A Béninese professor has also contributed, in 2005, to a groundwater course at UND, as well as to a 2005 UND faculty/student field experience in hand pump repair in the country of Haiti.

The nitrate samples collected in 2003 led to initial indications that the nitrate observed in select wells was of human or animal origin (as compared to synthetic fertilizers). Hence, substantial effort was focused on the question of identification of source of nitrate based on high-frequency (in time) monitoring of nitrate in select contaminated groundwater wells. For this purpose, graduate students from UAC and/or UND lived in the village of Adourékoman in the Colline region of Bénin for periods of up to 7 weeks in each of the summers of 2004–2007. These extended stays allowed the program to develop a strong understanding of the nitrate problem and to develop a training program through which the local population in Adourékoman could monitor their own water quality on a weekly basis.

New research efforts were initiated in southern Bénin in 2006 through extension of modeling efforts initiated through UAC. Based on an initial numerical model of the southern aquifer system developed by UAC and another partner (Boukari et al., 2008), the ongoing effort is focused on developing sensitivity measures on the original model, extending this model through consideration of transient conditions and density dependence, and field efforts to characterize the contribution of shallow hydrogeology of coastal Bénin as a primary driver on the groundwater hydraulics (the field work being guided by the model).

Starting in 2007, the partnership has returned to its roots in development of new groundwater resources for rural villages in Bénin. Rather than continuing to perform its own drilling using the small drill rig, however, the partnership is collaborating with an existing government program to drill government-sponsored wells in a number of rural villages. This effort has opened the opportunity for the partnership to work with local villages in developing wellhead protection efforts.

## Details of Practical and Scientific Efforts

### Well Drilling

The well-drilling efforts of the partnership can be divided into two periods with significant insight developed from both periods. In the first period, the partnership attempted to train well-drilling crews from within the local population to use a small, rotary drill rig (an LS-100; http://www.lonestarbitinc.com/ls-100_details.htm) to drill local village wells for domestic water supply. The initial effort with this rig involved a training exercise in Houmbo, Bénin, where a well with approximate depth of 18 m was completed. Positive outcomes from this initial effort included the drilling of the well and the development of a close working relationship among UND, UAC, and CAO through the need to deal with a series of unexpected field set backs such as finding a replacement mud pump on short notice when the pump on the drill rig failed. This initial effort also highlighted a number of challenges among the partners, including finding common ground in dealing with questions from the community regarding their willingness to site the well in a location that was not their preferred location. While difficult at the time, dealing with these challenges strengthened the partnership and built a significant level of trust in the individuals involved in this program.

This initial period of drilling was extended in 2003 through drilling of a second well in Vovio, Bénin. The partnership experimented (successfully) in this case with transferring all training responsibilities to African partners through collaboration with a drilling group (Eau de la Vie, Togo, associated with Lifewater International) who led all training and pump installation. Although involved in initial planning, placement, and financing of this well, UND was not involved in any portion of the driller's training or drilling of the Vovio well. This effort illustrated the potential for transfer of the training effort to local organizations in Western Africa.

The second period of drilling was initiated in 2007. Through discussion within the partnership, and in particular through identification by DGEau of other alternatives for drilling deep water supply wells, an alternative strategy was adopted. Specifically, DGEau develops water projects in collaboration with local communities through a program that involves training representatives of the local community in water options. The representatives are then requested to select the level of water service desired by the community (e.g., improved hand-dug wells, drilled wells with hand pumps, or drilled wells with a local water tower and distribution system). The community is also requested to provide a small share of the financing of the new water system.

In the new drilling effort, the partnership was requested by DGEau to work with a number of local villages that would otherwise not be able to meet the minimum cost share. The partnership was able to use available financing to offset a portion of the community cost share. In return, the local communities were asked to work with the partnership in siting the new wells and in being open to discussing wellhead protection strategies for the new wells. This collaboration with the government allowed the partnership to leverage limited funding (equivalent to the funding used to drill the first two wells with the LS100) to support drilling of 19 groundwater wells equipped with hand pumps. Further, this collaboration provided training and water committees for each of these new wells.

Through these experiences with drilling, the partnership was able to assess two approaches to developing new wells for village water supply. Although the long-term results from the second series of well installations cannot yet be fully assessed (as the wells are being completed only as of the time of writing), the program experience suggests that, in general, the use of experienced drilling teams and established development programs provided greater efficiency and greater probability of both installing a successful well and establishing long-term use and maintenance. Specifically, the second period of drilling allowed greater confidence in both the village expression of need for the well and the siting of the well in an acceptable public location. Drilling via the government program also provided greater consistency between the hand pumps installed and the majority of hand pumps currently in use elsewhere in Bénin, thus allowing for easier future repair of the hand pumps on these wells. While it is recognized that this conclusion may not be generally transferable to other countries in Africa (depending, in particular, on the level of government support of drilling efforts), future efforts at well installation in Bénin by the partnership are likely to follow the second model (collaboration with the government program) rather than further efforts with training of local populations.

## Characterization of Elemental Chemistry

Between the years 2002 and 2004, a series of water samples were collected from domestic hand pump wells in central and northern Bénin (Fig. 1 – see Silliman et al., 2007, for details of the data collection and analysis methods). Analysis in the field involved measurement of a number of parameters including

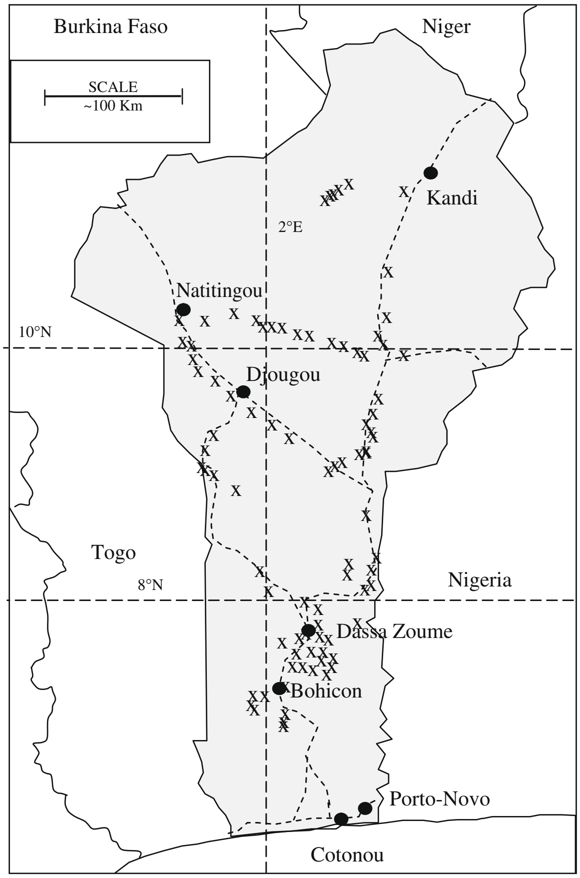

**Fig. 1** Map of Bénin showing approximate location of water samples collected from hand pump wells (from Silliman et al., 2007)

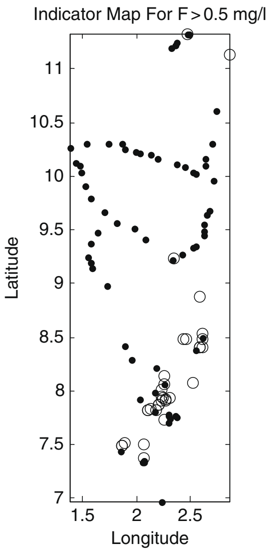

**Fig. 2** Indicator map for fluoride (*open circles* represent sample locations with concentration greater than 0.5 mg/l) demonstrating a region of elevated concentration in south-central Bénin. Similar results were obtained for a number of elements (Silliman et al., 2007)

pH and conductivity. Following return to the laboratory (samples were filtered and acidified in the field for preservation), the samples were analyzed using ICP-MS, ICP-OES, and specific ion methods to provide concentrations for approximately 30 elements (including both major and trace elements) (Silliman et al., 2007). Data analysis involved exploratory methods, spatial analysis (semivariograms), and principal component analysis. A primary result of this effort, as indicated by the indicator variable result shown in Fig. 2, was the identification of a region in south-central Bénin (the Colline region) where the groundwater chemistry is highly variable with elevated concentration of fluoride, uranium, and a number of major elements. Study continues in this region in attempt to determine how the geology in this region has led to the observed elevated concentrations, with particular emphasis focused on the source and fate of uranium in the water phase.

## Characterization and Monitoring of Nitrate

As indicated above and independent of the elemental analysis, DGEau had identified the Colline region as a region subject to contamination with nitrate. As a result, the partnership has pursued a series of studies involving nitrate in the Colline region. Water samples for isotopic (N and O) analysis were collected in 2003 and 2007 from a number of wells for which analysis indicated elevated nitrate. As shown in Fig. 3, a consistent pattern is observed in the data suggesting that the source(s) of nitrate are derived from human or animal bodily waste products. This result is also consistent with the field observation that the highest nitrates were associated with village centers rather than zones of agriculture. Finally, the apparent trend in the isotopic composition is consistent with the expected denitrification line (e.g., Chen and MacQuarrie, 2005), thus suggesting that the region may be subject

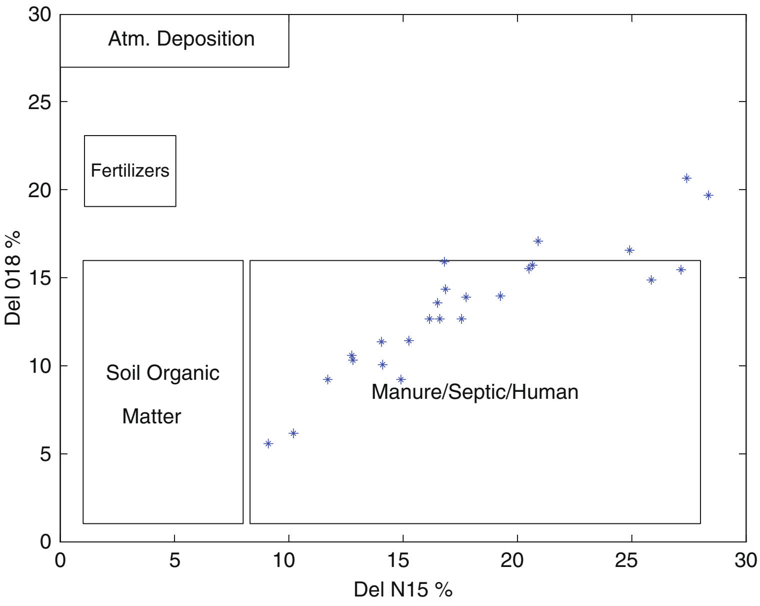

**Fig. 3** Nitrogen and oxygen isotope data from the Colline Department in Bénin. All samples from hand pump wells with elevated nitrate concentrations. Source compositions from Rock and Mayer (2002)

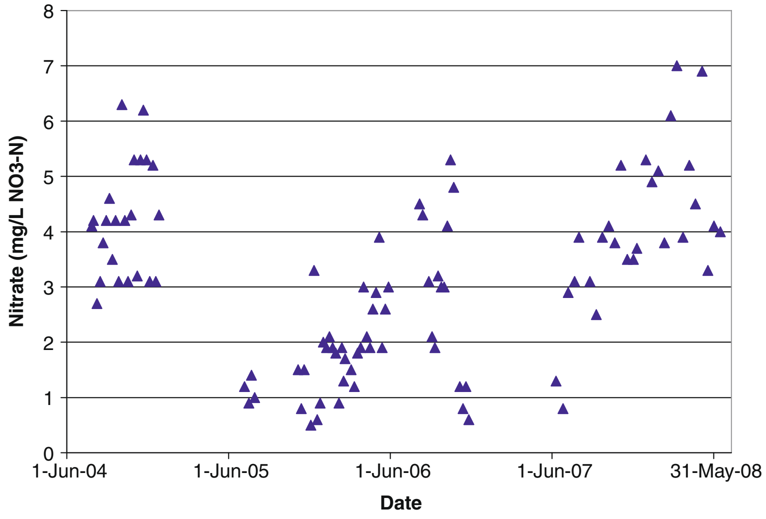

**Fig. 4** Nitrate data from well Ayewa in Adourékoman, Bénin, as collected by one of the local sampling team using a nitrate colorimeter. These results demonstrate the level of details made possible through training of the local monitoring teams (after Crane et al., 2009)

both to nitrate contamination and denitrification processes.

Based on these isotopic results, a second phase of the nitrate monitoring program was pursued in an effort to obtain measures of the temporal variation in the nitrate concentration within local wells in the Colline region. As the partners lacked the resources necessary to pursue weekly sampling at these wells with their own personnel, a program was initiated in a group of local villages (initiated in the village of Adourékoman) through which teams from the local population were trained to use simple test equipment (test strips and a colorimeter) to monitor basic aspects of their own water quality (nitrates, pH, hardness, ammonium, phosphate, and total metals) on a weekly basis.

As described in Crane et al. (2009) and Crane (2006, 2007), the effort to train local monitoring teams involved extended interaction of UAC and UND graduate students with the local population (several weeks per summer over several summers) to establish the monitoring program. Accuracy of measures of nitrate was monitored through requesting the local population to run (on a biweekly basis) blind nitrate standards. Based on this assessment, confidence was established that the local monitoring teams were consistently applying the field measures both during periods of supervision and between field visits by students within the partnership.

Following training, and subject to periodic review of methods, the monitoring teams performed weekly sampling for nitrate, pH, ammonium, phosphate, hardness, and total metals using test strips. The nitrate concentration was also measured using a dedicated colorimeter (see details in Crane et al., 2009; Crane, 2006). As of the time of writing this chapter, select teams have continued monitoring for a period of approximately 4.5 years. Figure 4 shows the type of detailed temporal variation in nitrate concentration that has been obtained through this effort. Further, theoretical arguments (Crane, 2007; Crane and Silliman, 2009) have shown that this type of local-level monitoring program may present opportunities for gathering high-value data sets in situations in which high-frequency monitoring cannot be accomplished by experts (due to time or financial resource constraints). Finally, initial success in this program has allowed extension of this monitoring program to additional villages in the Colline region.

## Modeling in Southern Bénin

The newest effort within the partnership is modeling of groundwater flow in the vicinity of the well field that supplies water for Cotonou, Bénin (Cotonou is the largest city in Bénin and is located on the southern coast). Based on foundational modeling pursued by UAC and DGEau in collaboration with a European partner (Boukari et al., 2008), the ongoing research within the present partnership (primarily efforts by UAC and UND) has been focused on delineating sensitivities within the prior model, advances in the prior model, and need for further field characterization.

The base model for this effort was a seven-layer, finite-difference model (based on the MODFLOW series of models; McDonald and Harbaugh, 1988) covering a region of 30 km (N/S) by 26 km (E/W) in southern Bénin. The layers in the model were designed to coincide with assumptions regarding the physical aquifers and aquitards in this multi-aquifer system. Figure 5a shows a three-dimensional rendering of the distribution of the hydraulic conductivity (in m/day) in this original model. Results from this early model imply that the coastal region is a significant groundwater divide (due to assumed recharge in this low-lying region), thus protecting the well field from saltwater intrusion from the Atlantic Ocean, but implying threat of groundwater contamination from natural and anthropogenic contaminants associated with the coastal swamp areas and portions of a large southern lake (Lake Nokoue).

Based on this original model, UAC and UND have pursued refinement of the model through (i) refining the estimated distribution of aquifer sediments based

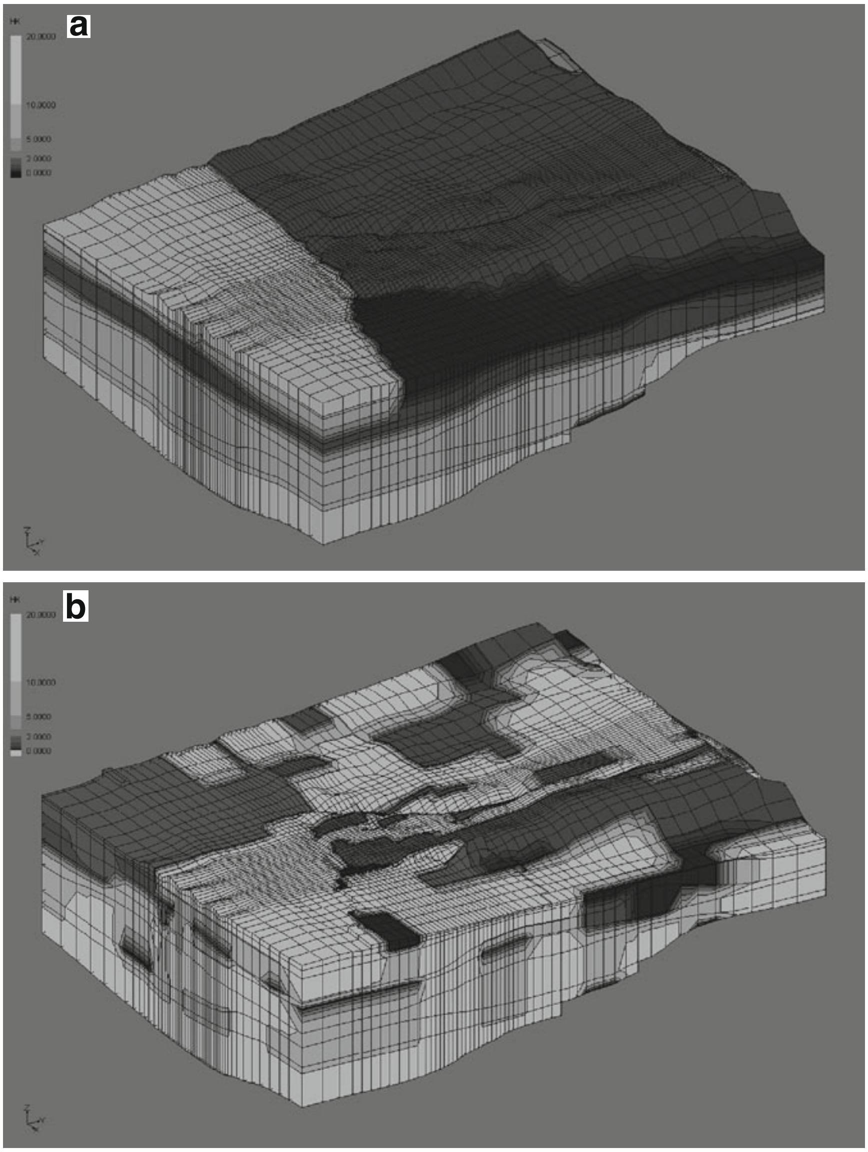

**Fig. 5** (a) Distribution of hydraulic conductivity for the original model of Boukari et al. (2008) with the *lighter shading* representing the higher hydraulic conductivities. Boundary conditions on the model included constant head cells along the northern boundary (the *right end of the grid* in this image), constant head boundaries along the upper layers on the southern boundary (*left end of the grid*), and zero flux boundaries elsewhere. The region underlying Lake Nokoue was also identified as a constant head boundary. (b) Distribution of hydraulic conductivity for an initial revision of the model (nine layers replacing the original seven layers) with the *lighter shading* representing the higher hydraulic conductivities. Boundary conditions were the same as for the original model

on well logs for southern Bénin, (ii) refining vertical discretization in the upper aquifer (to gain precision of flow prediction near Lake Nokoue and in the coastal region), (iii) examining the impact of the boundary conditions (particularly on the northern and southern portions of the grid), (iv) examining the spatial and temporal distribution of recharge/discharge in the coastal region, (v) determining sensitivity to estimates of groundwater parameters for the major aquifers, and (vi) determining sensitivity of the numerical solution in the region of the well field to assumed hydraulic conditions in Lake Nokoue.

The revised model contains nine layers (the upper aquifer now divided into three numerical layers). Based on the analysis of a large number of well logs, the distribution of hydraulic properties is significantly more complex than in the original. Figure 5b shows a rendering of the distribution of hydraulic conductivity within the modified model.

The northern boundary of the numerical grid in the original model was assumed to be a constant head. Numerical experiments were conducted to determine sensitivity of the solution near the well field to these conditions. For this boundary, the numerical experiments involved both varying the assigned constant head by approximately 50% and changing this boundary to a no-flow boundary condition. These numerical experiments demonstrated that the solution for heads and flow patterns in the vicinity of the well field were not significantly impacted by these changes to the northern boundary.

For the southern boundary, experiments were performed on both the location of the boundary (by moving the boundary further south into the ocean) and the distribution of constant head and no flow cells. As with the northern boundary, these changes had minimal effect on flow in the vicinity of the well field. The experiments on the boundaries, therefore, imply that no further refinement of these boundaries is needed until other more critical sensitivities are addressed/reduced elsewhere in the model.

In contrast to the experiments on the northern and southern boundaries, experiments on surface conditions assumed for the southern coast of Bénin indicated significant sensitivity of the flow patterns near the well field to the assumed distribution of recharge and discharge. Similar results were obtained in regard to sensitivity to conditions assumed in Lake Nokoue (in

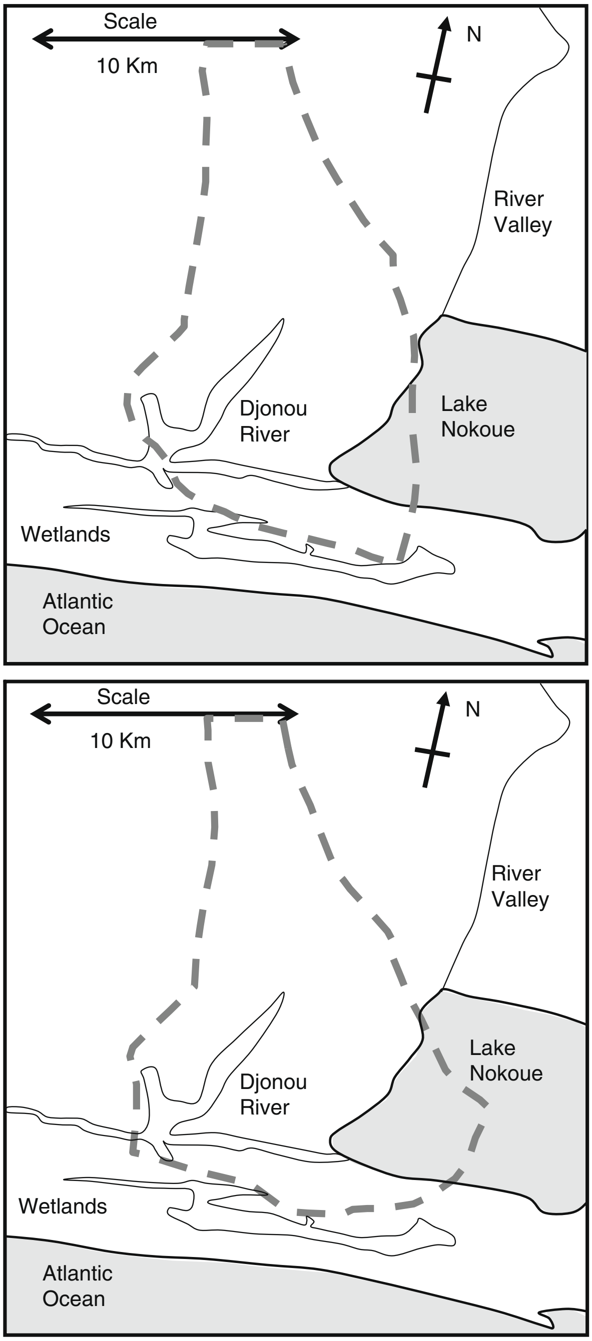

**Fig. 6** Capture zone (*dashed line*) from the well field. The approximate coastline of Lake Nokoue is shown as the location of the Djounou River and large coastal wetlands. The rotation of the map is to make orientation consistent with the orientation of the numerical grid. *Upper image* is the model shown in Fig. 5b with a constant head in Lake Nokoue of 0.5 m. The *lower image* is the same model but with the constant head increased to 2.0 m, resulting in substantially greater impact of Lake Nokoue on recharge to the well field

particular, the elevation of water level in the lake). For example, Fig. 6 shows the approximate capture zones for the well field with an elevation in Lake Nokoue of 0.5 m (the original value used in the model) and 2.0 m (approximate water level during the rainy season). These results show that Lake Nokoue is a significantly greater contributor to the capture zone of the well field under the second set of assumed conditions in the lake.

Finally, numerical experiments indicated that the solution for flow near the well field is sensitive to the distribution of the hydraulic conductivity in the aquifers in the vicinity of these wells (particularly vertical conductivity and connectivity between aquifer layers).

These sensitivity results indicate that substantial refinement of the model and field characterization are required to increase confidence in the numerical solution. These results led to initial efforts, during the summer of 2008, at field characterization of (i) hydraulic conditions in the southern coastal region, (ii) flux within the sediments of Lake Nokoue, and (iii) quantification of the hydraulic parameters in the aquifers.

## Student Involvement

Beyond the scope of the scientific aspects of the partnership, insight has been gained relative to the pedagogy of involving students in collaborative research in Bénin. In contrast to direct service projects, student (undergraduate and graduate students from both UND and UAC) efforts in Bénin have involved contribution to research efforts. This has included participation in the field sampling campaigns, leadership in the training and assessment within the monitoring program in the Colline region, participation in multiple short courses, and roles in the modeling and characterization efforts in the southern aquifer system. Although the details are beyond the scope of this chapter, these efforts on student development (both UAC and UND) are a major focus of the partnership with the goal of developing future capacity in both the United States and Bénin. The reader is referred to other manuscripts that provide the details and assessment of these efforts (e.g., Silliman, 2003, 2007, 2009; Silliman et al., 2005).

## Overview of Historical Strengths and Weaknesses of the Partnership Research Effort

As discussed in the previous section, the partnership has, over the past decade, been able to address a number of groundwater issues in Bénin. Brief reflection on the history of this partnership suggests four primary reasons for the long-term success of this program. First, the partners each bring complementary talents to the effort. For example, CAO brings expertise in sociological aspects of working with the local populations: this skill set was critical in selecting a local village for the monitoring program and in working with villages for the recent drilling efforts. DGEau has brought extensive knowledge of water supply and water quality issues in both rural and urban Bénin. UAC has brought expertise in Bénin hydrogeology, initial modeling efforts, and an interested graduate student body. UND has brought resources in analytical chemistry, expertise in groundwater characterization, interested graduate and undergraduates, and financial resources.

Second, each partner in the program has, during the past 10 years, suggested critical efforts leading to advance in the program. DGEau, for example, recommended investigation of the nitrate contamination. UND initiated the regional sampling effort, while UAC initiated the modeling efforts and provided the foundational model for the study. CAO continues to provide insight into working with both local populations and local government agencies. This reliance on strengths of each of the partners has created a level of trust and reliance on each of the partners that translates into projects that extend beyond the expertise of any of the individual partners.

Third, each of the partners believes in the philosophy that research results are developed through long-term commitment to the individual projects. As such, the partners have each been willing to be patient in each of the projects pursued over the past 10 years. This patience has allowed, for example, the development of trust in the partnership by the local populations in the Colline region monitoring effort.

Finally, the partnership has experienced and dealt with a number of challenges. These have included, among others, long-term problems with the original well drilled in Houmbo (due to political difficulties related to location of the well), equipment failure, changes in personnel, cultural misunderstandings, and medical challenges to the students involved in the program. These challenges have required each partner to evaluate their individual reasons for being part of the partnership, their willingness to deal with various challenges, and the value to the individual partner of their participation in the partnership. This, in turn, has resulted in relatively honest discussion of strengths and weaknesses of individual initiatives within the program and refocus of several of the program efforts to optimize contribution from, and minimize challenges to, each of the partners.

## Ongoing Vision of the Project

Based on the historical efforts and discussion among the partners, the vision for the efforts of the Bénin program over the coming 5 years is focused on five areas:

### Extension of the Modeling Effort for Southern Bénin

Primary efforts will be focused on further developing, calibrating, and verifying the model of flow and transport in the vicinity of the well field in southern Bénin. Four specific issues have been identified as focal points for the continuing efforts.

First, the model will be extended to a transient solution (to date, the model has been run under steady flow conditions). This extension will allow introduction of the seasonal variation in conditions in Lake Nokoue and the southern coastal region. This will further allow for modeling of long-term changes in rate of pumping from the wells in the well field.

Second, the model will be modified to include density effects along the coast and in Lake Nokoue. Of particular interest will be the interplay of seasonal variation in the depth and density (salinity content) of surface water (a function of the rainy versus dry seasons) and the rate/quality of recharge to the underlying aquifer system. Toward completing this characterization, a seasonal water quality monitoring effort is planned for both surface waters and groundwater in coastal Bénin and in Lake Nokoue.

Third, a series of pump tests are planned to help refine the estimates of the hydraulic properties in the aquifers, as well as to provide improved definition of vertical hydraulic connectivity among the aquifers. These tests will be performed with water withdrawal from existing groundwater wells and monitoring of water-level response in inactive wells screened both within the same aquifer and in overlying and underlying aquifers.

Finally, field characterization in both the lake and in the coastal areas will be used to better quantify spatial and temporal distribution of recharge (or upflow/discharge), as well as correlation of recharge with water quality. Toward this end, a series of field characterization campaigns are planned to provide spatial/temporal measures of hydraulic, thermal, and chemical signatures along coastal Bénin and in Lake Nokoue. These were initiated in the summer of 2008 through the use of falling-head permeameters and groundwater sampling utilizing a manual direct-push drilling method.

### Nitrate Characterization and Remediation

DGEau has expressed interest in extending the local-scale monitoring program to additional villages, but as an activity of this government agency rather than a research function of the partnership. Hence, the partnership is developing training and support materials to allow technology transfer of these methods to personnel in the local DGEau offices. The training will be focused on three goals: (i) providing the DGEau teams with the ability to understand, apply, and purchase appropriate technology methods for village-level water quality monitoring, (ii) creating training teams at the local DGEau offices that are capable in turn of training water monitoring teams in local villages, and (iii) establishing the ability among the DGEau offices to assess the results (using graphical and statistical methods) of village monitoring efforts.

Specific to Adourékoman, Bénin (the location of the original local monitoring effort), the program intends to work with the local population in an effort to reduce the concentration of nitrate in the village's three wells. Primary among the efforts to be pursued will be working with the local population to adjust hygiene practices: specifically, the team will work both to construct and encourage use of latrines at appropriate locations relative to the wells, the fractured rock geology, and village activities. Further, the program will study, in collaboration with the local population, practices involving corral and watering of local livestock and the potential that these practices contribute to the nitrate contamination. Finally, the program will collaborate with the village population in identifying alternatives for garbage disposal (currently in local garbage pits or abandoned hand-dug wells) in order to lower the probability that disposal contributes to the groundwater contamination.

## Development of Thermal and Chemical Tracer Methods for Source Identification in Wells in Fractured Rock

An important outcome of the previous efforts, not discussed above, is the desire of DGEau to rehabilitate a number of wells in the Colline region of Bénin that have been drilled for the purpose of domestic water supply, but have not been equipped with hand pumps due to observed natural (commonly fluoride) and anthropogenic (commonly nitrate) contamination. Critical to rehabilitating these wells is identification of the source or sources of contamination that are currently contributing to the well, and for the anthropogenic contaminants, study of the potential to eliminate or reduce the source(s) of contamination. Due to the complexity of delineating flow pathways in fractured rock, thermal and chemical tracer techniques are being studied that may provide field tools whereby contamination sources can be reliably identified (thus allowing the potential for elimination of the contamination and rehabilitation of the well). Of particular interest will be studies of the use of artificial chemical tracers and/or vertical temperature profiling. Chemical tracer methods will be used to provide positive indication of connection between a potential source of contamination and a well. Temperature monitoring will be used for indirect indication of depth and timing (relative to precipitation events or artificial recharge) of vertical flow in the annular space of the shut-in wells (e.g., Cady et al., 1993; Silliman and Robinson, 1989).

## Continuing Efforts to Drill New Groundwater Wells for Rural Villages

While not a central focus of the research efforts, the program will continue to pursue the drilling of new groundwater wells in rural regions of Bénin as funding becomes available. Of particular interest will be the development of groundwater resources in southwestern Bénin where prior efforts at installing groundwater wells have been limited. CAO is anticipated to adopt an increasing role in these efforts, particularly in terms of the training efforts with the local population.

## Education

The partners intend to continue to extend international educational initiatives through collaboration among faculty and students from Bénin and the United States. Particular focus will be placed on continuing collaborative research opportunities for the Bénin and US students involving short courses, modeling efforts, and field characterization efforts.

### Conclusions

The Bénin program partnership has allowed, over the past decade, projects involving drilling of water supply wells, modeling of groundwater resources, monitoring of groundwater quality (in collaboration with a local population), and building educational collaborations. The extensive history of collaboration among the partners allows development of a vision for future efforts focused on developing, protecting, and maintaining groundwater resources in Bénin. These future efforts will range from modeling groundwater flow in southern Bénin as a management tool for water supply, to transferring water quality monitoring efforts to the Bénin government agency tasked with management of rural water supply, to educational efforts to build research and management infrastructure in Bénin and the United States. This vision will be pursued, in part, through collaboration with the UNESCO International Year of Planet Earth.

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# Groundwater Artificial Recharge Solutions for Integrated Management of Watersheds and Aquifer Systems Under Extreme Drought Scenarios

J.P. Lobo Ferreira, Luís Oliveira, and Catarina Diamantino

**Abstract**

This chapter addresses groundwater artificial recharge solutions for integrated management of watersheds and aquifer systems under extreme drought scenarios. The conceptual idea of Aquifer Storage and Recovery (ASR) is considered here as one of the science-based mitigation measures for climate variability and climate change in many parts of the world. Towards a sounder selection of the most appropriate method to build ASR facilities, several experiments have been carried out in the southern Portuguese region of the Algarve during the European Union-sponsored 6th Framework Programme for Research, Project GABARDINE on "Groundwater Artificial Recharge Based on Alternative Sources of Water: Advanced Integrated Technologies and Management". The values obtained for infiltration rates available on the multiple experimental facilities depend not only on the hydraulic heads but also on the type of experiments and on the type of soils available regionally. The results gathered allowed the drawing of several original charts on infiltration rates that will be presented at the end of this chapter. The aim of all these experiments was to improve the knowledge on real case studies that involve application of different AR methodologies to assess the parameters needed to develop optimization models. The model may incorporate restrictions and parameters of the objective function values evaluated in the experiments described above. The results presented in this chapter allow the selection of the most appropriate AR techniques aimed at the maximization of groundwater quality improvement, while minimizing the cost. In parallel a new method, called GABA-IFI, aimed at preliminary identification of candidate areas for the installation of groundwater artificial recharge systems, was developed for the European Union-sponsored 6th Framework Programme for Research Coordinated Action ASEMWATERNet, a "Multi-Stakeholder Platform for ASEM S&T Cooperation on Sustainable Water Use" based on previous studies developed for five Portuguese Watershed Plans. This new method was applied both to Campina de Faro aquifer and to Querença-Silves aquifer in the Algarve. This chapter addresses the achievements of this project.

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**Keyword**

Managing artificial recharge • Groundwater • Infiltration basins • Integrated management • Drought mitigation • GABA-IFI • Algarve

## Introduction

This chapter is based on groundwater artificial recharge (AR) solution for integrated management of watersheds and aquifer systems under extreme drought scenarios. Based on a lecture presented at the IYPE Workshop held in Oslo, August 2009, the conceptual idea of Aquifer Storage and Recovery (ASR) is being considered as part of the solution towards scientific-based mitigation measures to climate variability and/or climate change in many parts of the world.

Also in Portugal, two EU-sponsored 6th Framework Programme for Research Projects have addressed this topic, namely GABARDINE Project on "Groundwater Artificial Recharge Based on Alternative Sources of Water: Advanced Integrated Technologies and Management" and Coordinated Action ASEMWATERNet, a "Multi-Stakeholder Platform for ASEM S&T Cooperation on Sustainable Water Use".

The main objectives of the Gabardine Project were as follows: (1) to identify alternative water sources and study the economic and environmental feasibility of its use in semi-arid areas, in the context of an integrated water resources management; (2) to study the aquifers as a main water source for both seasonal and long-term storage of these alternative water sources; and (3) to improve knowledge about possible methods to introduce these water sources in the aquifer, namely through artificial recharge.

Alternative water sources for groundwater artificial recharge may include the superficial runoff surplus produced during flash flood events, treated urban wastewater, desalinated water surplus or water import.

The development of this study approached several issues related to the subject like precipitation rate analysis, both water and recharge balance, identification of the potential alternative water sources intended to recharge the aquifer and assessment of existing technologies for its use, development of tools aimed for managing groundwater resources considering artificial recharge, assessment of aquifer vulnerability and characterization of the unsaturated zone. Several artificial recharge devices have been developed and implemented in this project.

Four case studies were selected for real experiments of groundwater artificial recharge systems: Llobregat Valley (Spain), Campina de Faro (Portugal), Israel and Palestine (Gaza) and Thessaloniki Bay (Greece). These areas face several problems of water supply due to overexploitation, saline intrusion or pollution resulting from wrong agricultural practices. The artificial recharge system resorted to alternative water sources as a viable methodology to solve or minimize these problems.

On the other hand, the overall goal of the Coordination Action ASEM WaterNet is to promote science and technology cooperation between Europe and Asia on water resources management by focusing on five main issues: river basin management, water use efficiency in agriculture, floods, pollution, governance.

Considering these main areas of water research, the sub-objectives of the Platform will be the following:

- to promote water management at the basin scale seeking for transparency and equitable and sustainable benefits;
- to improve efficiency in agriculture in order to increase conditions of life and ensure a sustainable use of water resources;
- to develop prevention of floods, as well as mitigation of their effects, and preparedness;
- to increase knowledge on soil and aquifer pollution, in order to propose prevention and remediation strategies;
- to explore and promote best practices in water governance, including human dimension and participatory approaches.

Pyne (1995) defines the ASR as "the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed".

This technique avoids the construction of extra wells, facilities or treatment plants and therefore there is an increase in economical efficiency (Pyne, 1995). ASR schemes are used in many parts of the world with a focus on two countries, USA and Australia. Australia, due to the persistent drought years of the first decade of the new millennium, is well-developed in the area with more than 300 wells of ASR, national legislation only for this issue and a national technical guide for ASR.

According to the Australian ASR and ASTR (T stands for transport) Guideline (Dillon et al., 2006) an ASR scheme should contain the following items:

– channel to shift the water from the water source to the scheme;
– different control and monitoring structures;
– a detention pond or tank to retain water after the recovery;
– wetlands or detention ponds to store the water to be injected;
– some form of water treatment;
– a valve or anti-cavitation device.

Dillon et al. (2006) mention that the selection of an ASR site can be made according to four requirements:

1 An area with a demand of water with the quality that can be recovered
2. A good access to an acceptable source of water for injection
3. Available areas to construct basins and a treatment plant
4. An aquifer not only with acceptable storage capacity and water quality but also with an adequate injection rate and capacity to recover stored waters.

The Australian ASR and ASTR Guideline (Dillon et al., 2006) advises nine guiding principles necessary to achieve best practices for ASR and ASTR. They are adopting a risk management approach, preventing irreparable damage, demonstrations and continuous learning, adopting a precautionary approach, establishing water quality requirements, rights of water bankers and recoverable volume, finite storage capacity of aquifers and interference effects between sites, highest valued use of resources and community and other stakeholder consultation.

Towards a sounder selection of the most appropriate area to build ASR facilities, a new method was developed at LNEC, Portugal, the index Gaba-IFI (Oliveira, 2007). This method will be explained in this chapter as well as the values expected to be found in the rates of infiltration of the facilities. The rates have been experimentally measured in the southern Portuguese region of the Algarve.

## Why Do We Need to Consider Droughts and ASR Facilities in Portugal?

A drought is a natural phenomenon in the Mediterranean region. It is not a fatality but rather a recurrent situation requiring solutions and mitigation measures.

Natural disasters like floods have instantaneous repercussions. Droughts on the contrary have a longer duration and effects may last much longer, being almost impossible to assess when a drought starts and when it is over. Another characteristic of droughts is the area covered by the phenomenon, as it hits vast areas and it is quite complicated to delimitate the area covered.

The impacts and consequences of a drought can be felt in direct ways (e.g. inadequate water supply to the population, agriculture and industry and the water availability in the soil causing agricultural/vegetation damages) or indirect ways (increase of the concentration of pollution in water bodies and the decrease of groundwater levels with the possibility of saline intrusion).

In a common sense, droughts are defined as "lack of water". However, its definition is much more complicated. It is important to state that there is no universal definition of droughts. Its definition depends on the technical speciality and on the geographical location of the person that is defining it, e.g. drought definition of a meteorologist is different from that of an agro-specialist.

Scarcity of water instead is a characteristic of several areas and can be influenced by humans in a temporary or permanent occurrence, being divided into four types as presented in Table 1.

**Table 1** Conceptual types of scarcity of water

| | Scarcity of water | Origin | |
|---|---|---|---|
| | | Natural | Anthropogenic |
| Time of occurrence | Permanent | Aridity | Desertification |
| | Temporary | Drought | Lack of water available |

A drought occurs when the natural event of scarcity of water is temporary (yet for a long period). A bad water management can result in lack of water availability for water users.

A determinant is a variable that establishes the type of analysis that should be made to understand and characterize a drought (Santos, 1981). Several authors divide drought into three types according to its determinant: meteorological drought (determinants are, for example, temperature or precipitation), agricultural drought (determinants are, for example, humidity in soil or piezometric level) and urban drought (the determinant is the volume of water available in structures with the purpose of water supply).

The product of the probability of a natural disaster by the vulnerability of the region gives the risk of the society to that adversity. Regional characteristics can be more or less amplified by humans (e.g. the retention time of water in the area can be enlarged after the construction of a dam).

There is a huge difficulty in avoiding or predicting droughts and so it seems advisable to the authors to fulfil the objective of the society in minimizing the risk of droughts and to concentrate on enforcing risk plans that aim at reducing the vulnerability of the region to droughts.

The most used index in Portugal is the *Standardized Precipitation Index* (SPI) created by McKee et al. (1995), based on the *Palmer Drought Severity Index* (PDSI, Palmer, 1965). The index is the standardization of the precipitation using the ratio between the deviations of the values of precipitation and an average value in a reference period of time with the standard deviation of the reference period of time. It was designed to operate in different time scales: 1, 2, 3, 6, 9, 12, . . ., 24 months. Table 2 presents the SPI intervals and the respective drought classification.

In Portugal the characterization of droughts has been made since 1942 using precipitation data. Using the SPI-12 it is possible to say that since the agricultural year (September to August) of 1943/1944 there have been 5 years considered as drought in most of the country, with two extreme dry years (Domingos, 2006). Another example of such characterizations can be seen in Fig. 1. In this figure rows correspond to years (1969–2005) and columns correspond to northern districts (on the left side) and southern districts (on the right side). One may easily see in this SPI-12 index table, computed for all Portuguese mainland districts, i.e. not for the Azores and Madeira archipelagos, a sequence of blue lines (i.e. wet years) followed by a frightening sequence of red rows (i.e. dry years) that seems to become more solid as time proceeds and also more compact along the districts from north to south. Something has to be done on adaptation measures to this reality. It is time now to proceed with scientific-based appropriate methodologies to avoid recurrent scarcity.

**Table 2** Standardized precipitation index and drought severity

| SPI | Severity of drought |
|---|---|
| 0.99 to –0.99 | Near normal |
| –1.00 to –1.49 | Moderately dry |
| –1.50 to –1.99 | Severely dry |
| ≤2.00 | Extremely dry |

## Average Precipitation and Groundwater Availability in the Algarve

The southern region of Portugal is the Algarve with an area of 4,995.2 km$^2$ and a permanent population of 405,380 inhabitants. Beautiful beaches, warm temperature in winter and hot summers and great touristic condition (e.g. excellent golf courses) make Algarve one of the most attractive vacation places in the world (Fig. 2).

Geographically it is a low altitude zone, with the highest elevation being 906 m at Monchique Mountain. This characteristic makes the construction of large dams difficult. On the contrary the region is rich in aquifer systems (17 systems identified). These two reasons explain why until a decade ago almost all water in Algarve was supplied from groundwater.

The average precipitation in the Algarve is around 500 mm, the highest zones having an annual average precipitation higher than 1200 mm and the littoral zones having values around 400 mm.

The variability of the total population over the year is the most evident social characteristic. While in winter the population is, more or less, 400,000 inhabitants, in summer thanks to the tourists and visitors (around 6,000,000 persons do visit the Algarve per year) there is a huge increase in population.

The Querença-Silves is a 318 km$^2$ aquifer system, the largest of the Algarve, located in the municipalities

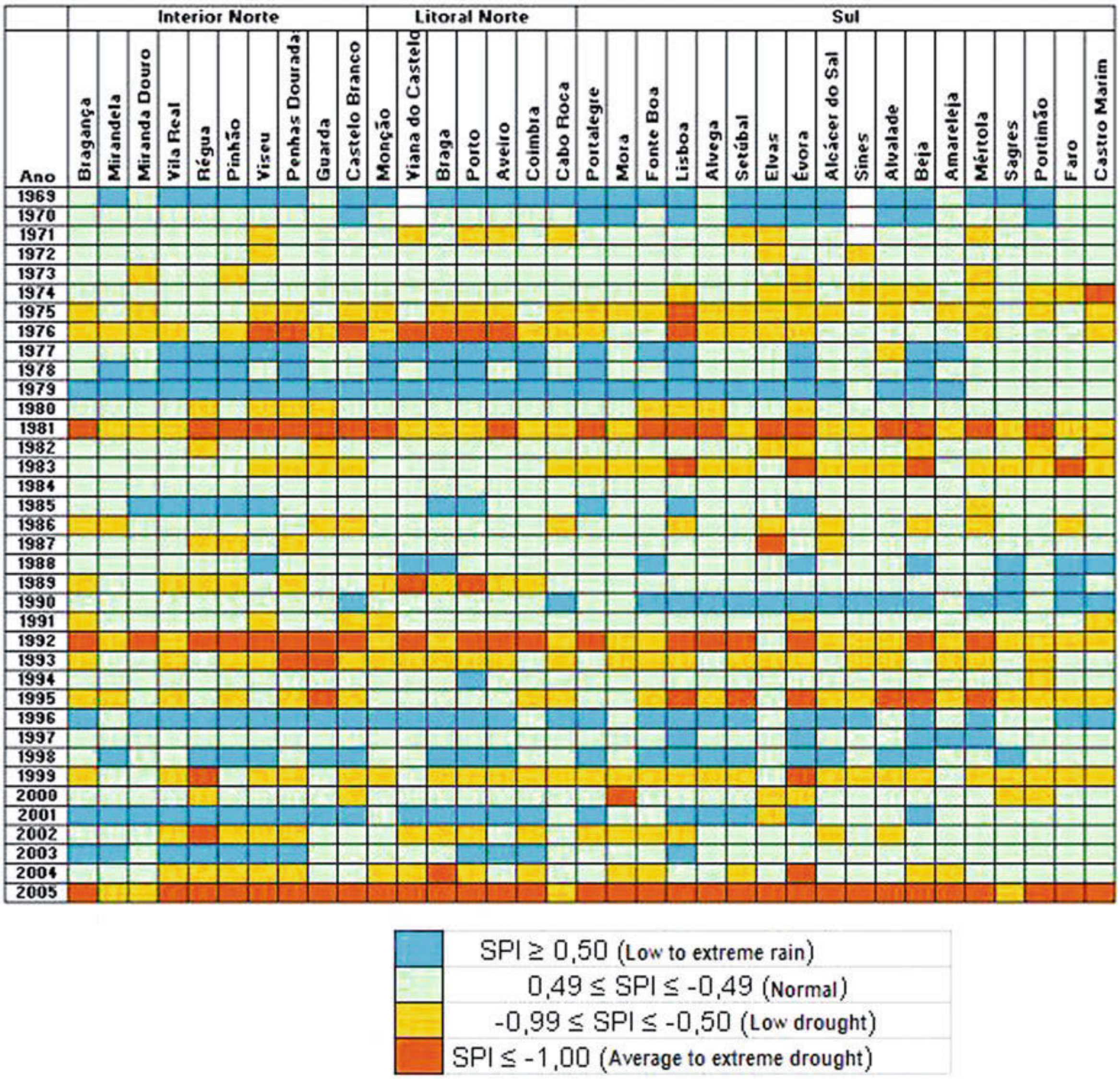

**Fig. 1** SPI-12 values computed for selected municipalities (columns) from 1969 to 2005 for the northern coastal zone and interior regions of Portugal as well as for the southern region

of Silves, Loulé, Lagoa and Albufeira (Central Algarve) (Figs. 2 and 3).

The aquifer is mainly composed of karstified Lower Jurassic (Lias-Dogger) dolomite structure. The structure from the Jurassic is formed by confined to unconfined aquifer system. The aquifer system is limited by two less-permeable structures: the *Grés de Silves* in the north and the marl-limestone and marls of the Calovian-Oxfordian-Kimeridgian in the south (Almeida et al., 2000).

According to the characterization of the Querença-Silves aquifer system by Almeida et al., 2000 the hydraulic parameters are heterogeneous and the productivity values are high. Table 3 presents the calculated values of productivity (l/s). The transmissivity has values ranging from 83 to 30,000 m$^2$/day and the storage coefficient of the aquifer system is also heterogeneous, with values ranging from $5\times10^{-3}$ to $3\times10^{-2}$. The hydraulic conductivity on the west side (west of the Quarteira fault) of the aquifer is 50 m/day,

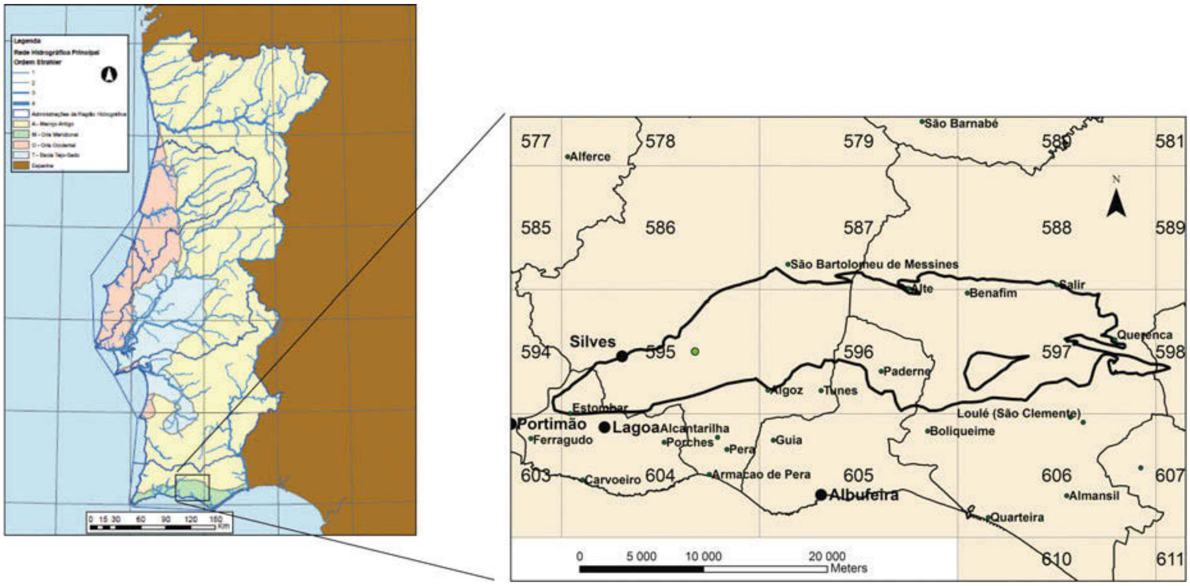

**Fig. 2** Querença-Silves aquifer system and its localization in Portugal

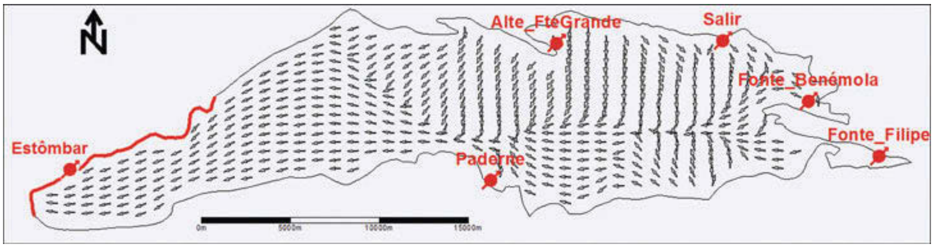

**Fig. 3** Model of the flow direction of the Querença-Silves aquifer system

**Table 3** Statistics of the productivity of the Querença-Silves aquifer system

| Average | Standard deviation | Minimum | Q1 | Median | Q3 | Maximum |
|---|---|---|---|---|---|---|
| 12.2 | 9.8 | 0.0 | 5.8 | 11.1 | 16.6 | 83.3 |

on the central side 1m/day and on the east side (east of the fictitious line) 0.05 m/day.

The characterization of the water flux in the aquifer system is quite complex. The aquifer system has a considerable number of data but there is no consensual piezometric map due to the heterogeneous behaviour of the aquifer and the lack of data in some areas.

Figure 3 shows the flow of the Querença-Silves aquifer system obtained through models applied to the aquifer (Monteiro et al., 2006).

Several studies have been made to assess the annual recharge of the aquifer. INAG (2001) presents the value 70 ± 17 hm$^3$/year considering the percentage of recharge to be around 40 ± 10% of the precipitation. An average recharge value may be considered as 93 hm$^3$/year. These are average values using the average precipitation values in the area; therefore, when the precipitation is much smaller (e.g. the hydrological year of 2004/2005 when precipitation was more than half the average) the recharge is also much smaller.

Assessing 69 wells within the aquifer for the year 2002 an estimation of withdrawal of 6.2 hm$^3$/year was computed for the municipalities of Silves, Lagoa, Albufeira and Loulé. This value was higher during the drought years of 2004/2005.

The year of 2004/2005 was terrible in terms of drought severity. During that period the Querença-Silves aquifer system was the one envisaged

**Table 4** Volume of water extracted from the Querença-Silves aquifer system during the year 2004/2005 (Monteiro et al., 2006)

| | Volume of water withdraw ($\times 10^6$ $m^3$/year) | Percentage |
|---|---|---|
| Agriculture | 23.79 | 47.31 |
| Urban supply – regional pipe system of Algarve | 14.25 | 28.34 |
| Urban supply – local municipalities | 12.25 | 24.36 |
| Private users | Not available | – |
| Total | 50.29 | 100 |

to overcome water supply deficits. Monteiro et al. (2006) estimated a water extraction volume higher than $50.29 \times 10^6$ $m^3$/year during the drought period. Table 4 shows the total volume of water extracted during the drought period of 2004/2005, divided by the different water users.

The volume for agriculture is an approximation, computed for the area of irrigation, considering an average consumption of 600 mm/year.

## The GABA-IFI Index: A New Method for the Selection of the Best Area for the Installation of an ASR

### Introduction

The index named GABA-IFI (GABA from GABARDINE Project and IFI from the *Indice de Facilidade de Infiltração* infiltration facility index, in Portuguese) developed for Portuguese Watershed Planning by Oliveira and Lobo Ferreira (2002) is composed of three parts that are combined to produce the final result: (a) GABA-IFI_N, concerning natural characteristics of the groundwater medium, (b) GABA-IFI_€ concerning economic aspects and (c) GABA-IFI_SOC concerning social impacts.

GABA-IFI_N considers three aspects: the recharge rate, the aquifer storage ability and the time that the water remains in the aquifer system before being discharged. The larger the values the better the conditions for artificial recharge are met.

The three sub-indexes may be combined in different ways depending on the weights that a decision maker may give to each component of the sub-index.

### Sub-index GABA-IFI_N

An area is considered a good area for artificial recharge in terms of natural characteristics if three objectives are maximized: (1) residence time of water in the aquifer, (2) enough space in the aquifer to store the recharged water and (3) appropriate recharge rates.

#### Residence Time of Water in the Aquifer

This objective is described by the parameter *Dist: Distance to the groundwater discharge area*. This parameter guarantees the maximization of the residence time of the water in the aquifer; larger distances make areas more appropriate for artificial recharge.

The value of GABI-IFI_N obtained for this parameter should take into account the time of residence; therefore, the natural characteristics of the aquifer must be understood: groundwater flow paths, hydraulic conductivity, piezometric gradient and the effective porosity. Since these characteristics depend on the aquifer, this parameter is differently characterized for each aquifer system.

Four classes are considered, related to the residence time (limits of 6 months, 1 year and 3 years).

The application of the methodology to the west part of the Querença-Silves aquifer system is considered with values of 50 m/day for hydraulic conductivity, 0.01 for effective porosity and 0.001 for average piezometric gradient and flow direction from east to west.

With these characteristics, the table of conversion for this parameter (Table 5) shows the result of the application. The mapping of Dist is shown in Fig. 4.

#### Enough Space in the Aquifer to Store the Recharged Water

The space available in the aquifer to store groundwater is indicated by the parameter *D: Depth to the water level*. Larger depths imply more space available for artificial recharge in the aquifer and avoid the problem of pounding or of artificial wetlands due to AR facilities.

The mapping of D is shown. The class ranges are the same as those used in the DRASTIC index for groundwater vulnerability assessment (Fig. 5). Table 6 shows the application of this parameter to the western part of the Querença-Silves aquifer system.

**Table 5** Dist rating as a function of the distance to the groundwater discharge area

| Dist | 1 | 5 | 8 | 10 |
|---|---|---|---|---|
| Distance (m) | <920 | [920–1825] | [1825–5475] | >5475 |
| Time of permanence | <6 months | [6 months–1 year] | [1 year–3 years] | >3 years |

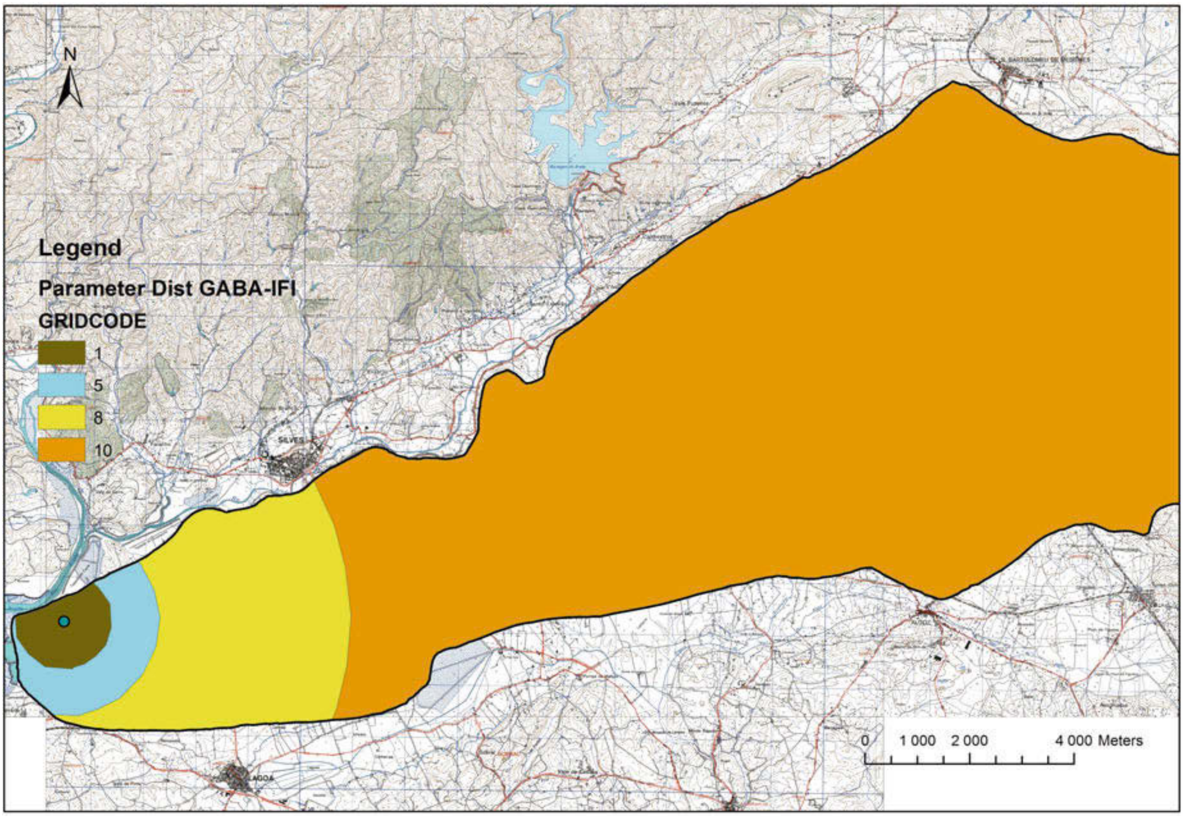

**Fig. 4** Characterization of parameter Dist

### High Recharge Rate

The recharge rate is related to two processes that considered alone would not describe it in the best way: (1) the time the water takes to arrive to the water table and (2) the capacity of the aquifer to "spread" the water recharged from the recharge area to the rest of the aquifer, given by its horizontal hydraulic conductivity.

### tt: Vertical Travel Time

It is necessary to calculate the travel time of the water in the vadose zone until it reaches the top of the aquifer. This parameter is calculated by dividing the distance to the water level by the vertical (saturated) hydraulic conductivity of the vadose zone.

The lower the travel time, the higher the likelihood for the water to reach the aquifer.

The conversion of the parameter tt is described in Table 7. The application is shown in Fig. 6.

### KH: Horizontal Hydraulic Conductivity of the Aquifer

The larger the horizontal hydraulic conductivity, the more easily the water recharged is "spread" from the recharge area to the rest of the aquifer, thus enhancing the recharge rate.

The conversion table of the parameter is equal to parameter C of the DRASTIC method and is presented in Table 8.

Figure 7 shows the results of the application of this parameter.

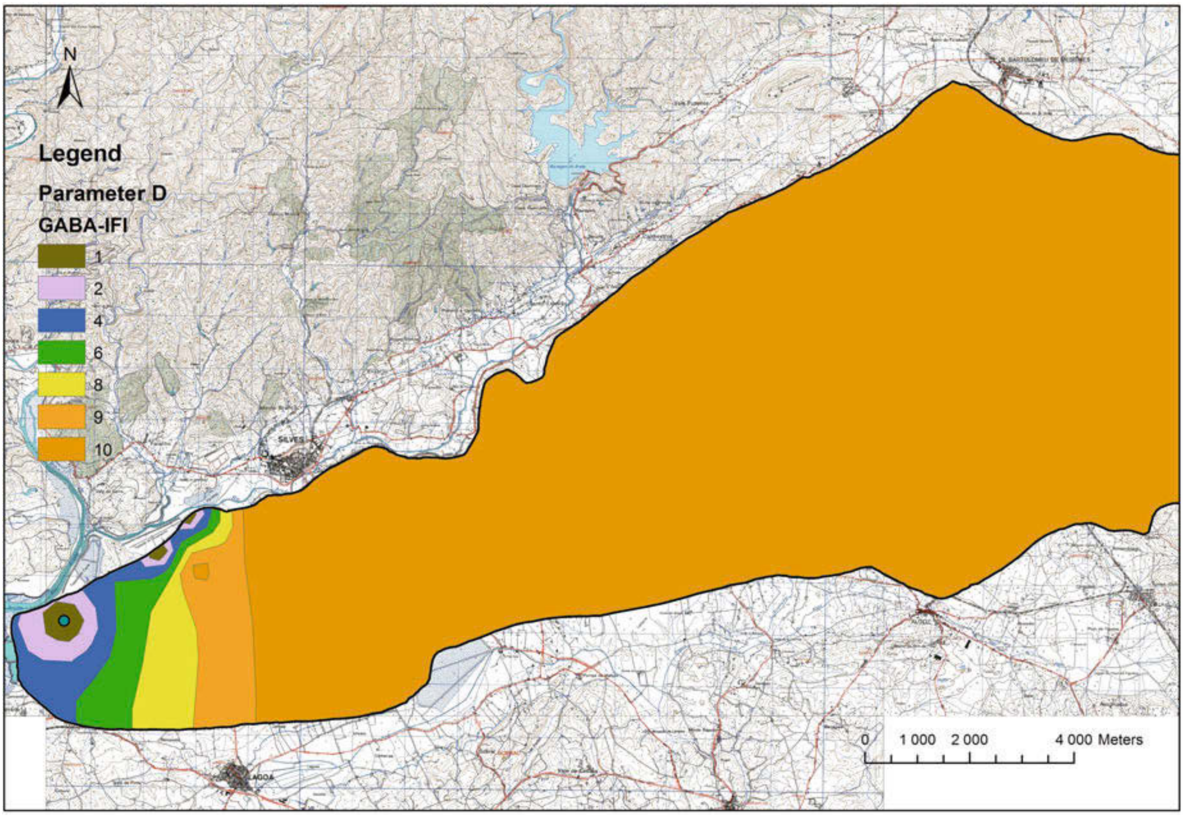

**Fig. 5** Characterization of parameter D

**Table 6** D rating as a function of the distance to the water table

| D | 1 | 2 | 3 | 5 | 7 | 9 | 10 |
|---|---|---|---|---|---|---|---|
| Distance to the water level (m) | <1.5 | [1.5–4.6] | [4.6–9.1] | [9.1–15.2] | [15.2–22.9] | [22.9–30.5] | ≥30.5 |

**Table 7** tt rating as a function of the vertical travel time

| tt | 1 | 3 | 5 | 8 | 10 |
|---|---|---|---|---|---|
| time | >7 days | [2–7 days] | [12 h–2 days] | [30 min–12 h] | <30 min |

### Computation of the Sub-index GABA-IFI_N

The three parameters are weighted equally. As the third objective (appropriate recharge rate) is described by two parameters, each one of these parameters is half-weighted. Thus, the sub-index GABA-IFI_N is calculated by the following equation:

$$\text{GABA - IFI\_N} = \text{Dist} + \text{D} + (1/2 \times \text{tt} + 1/2 \times \text{KH})$$

The sub-index varies between 3 and 30, where the higher values represent the more adequate areas for artificial recharge, in terms of natural conditions of the system.

The result of the application to the western part of the Querença-Silves aquifer system is shown in Fig. 8.

## Sub-index GABA-IFI_€

This sub-index intends to minimize two objectives:

(1) Transport of water from the water source to the artificial recharge area and

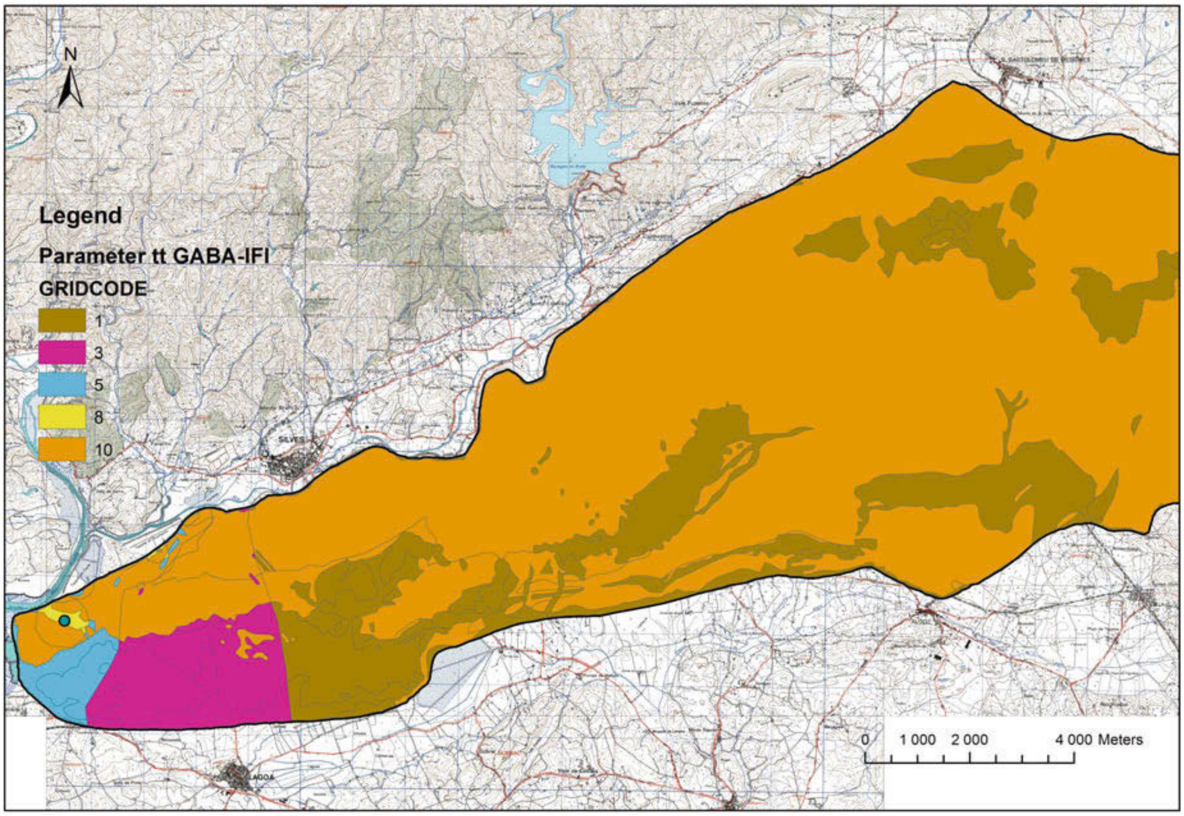

**Fig. 6** Characterization of parameter tt

**Table 8** KH rating as a function of the horizontal hydraulic conductivity of the aquifer

| KH | 1 | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| **Range (m/day)** | <4.1 | [4.1–12.2] | [12.2–28.5] | [28.5–40.7] | [40.7–81.5] | >81.5 |

(2) Construction and maintenance of the artificial recharge facilities.

The definition of this sub-index requires the identification of several sources of water for artificial recharge and the consideration of several alternatives for transporting the water to the more favourable places defined by using GABA-IFI_N sub-index. These alternatives depend on the topography, land use, distance to the water source, among others.

## Sub-index GABA-IFI_Soc

For this analysis it is important to be aware that society has a great impact on the decision of a project, and that the best area to build artificial recharge facilities is the one with the most positive impacts on the population that may benefit from the project. This may depend on the land use, the culture of a population, etc.

If we look carefully we may see a black dot with coordinates 26,000/1,800,000, in Fig. 8. The spot is located near the small village of Fonte de Louseiros, not only considered by Gaba-IFI index but also confirmed in the places visited by LNEC co-authors to be the best location for the implementation of new ASR facilities in the researched area.

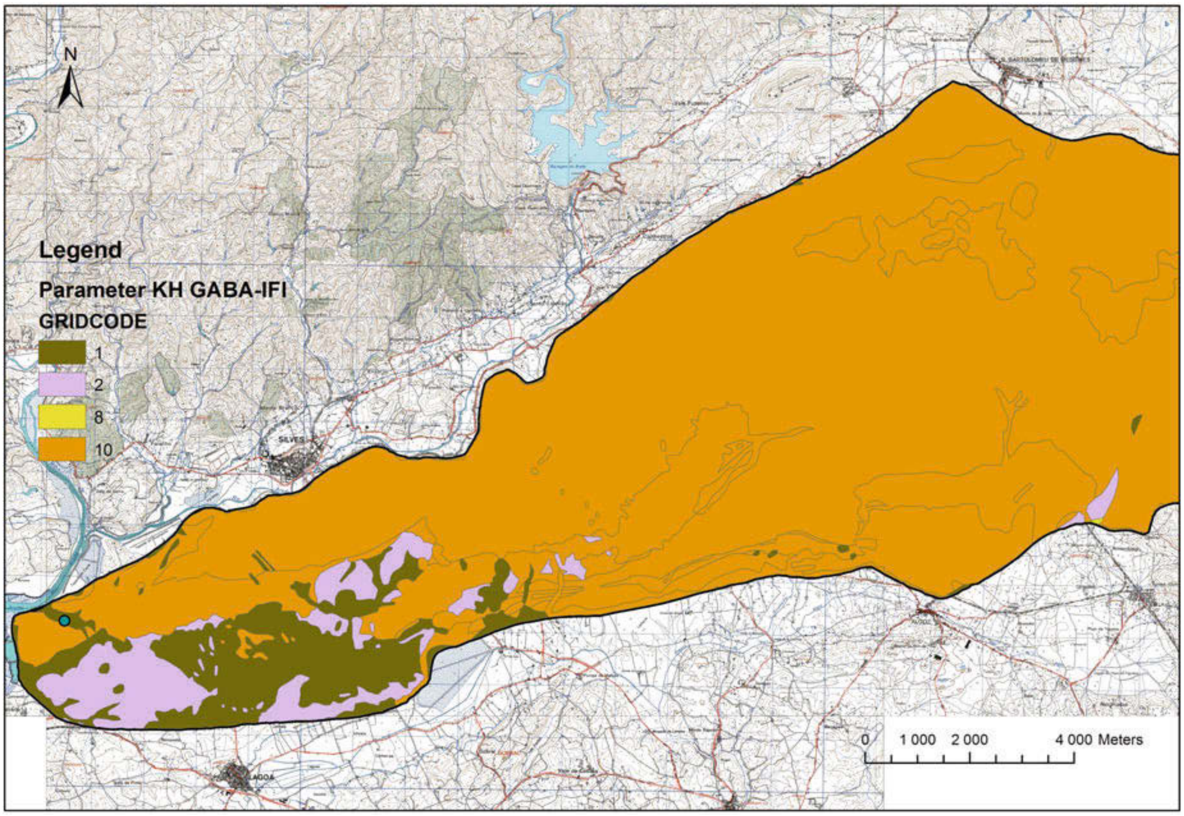

**Fig. 7** Characterization of parameter KH

## Where Will the AR Water Come from and When Shall We Be Able to Infiltrate It?

Now we advance in our artificial recharge query. This time the question is on water availability to run the new ASR facility, eventually to be located at Fonte de Louseiros. Where will the AR water come from and when shall we be able to infiltrate it?

As we said before, structures for aquifer storage and recovery are used in different parts of the world with several water sources. From the list of options three can be highlighted: the water surplus of wet years, treated wastewaters and the treated pluvial water of big cities.

This Portuguese case study for artificial recharge may be based on water surplus in wet years from the Arade dam. Using this water surplus for ASR we may avoid the problems of water scarcity in dry years. An advantage of the Arade dam is that it is located near the Querença-Silves aquifer.

Arade dam being the downstream dam on the Arade river (there is another big reservoir upstream, the Funcho dam), all water surplus above the capacity of the reservoir will be discharged, on wet years, and lost to the sea.

Before the severe drought of 2004/2005 there was one hydrological year that was very wet, the year of 2000/2001 (cf. http://snirh.inag.pt). This year had, for the area of the Querença-Silves aquifer system, an annual precipitation of 835 mm in comparison with the average annual precipitation of 670 mm/year. As year 2000/2001 was extremely wet, several dams reached the maximum water level and were forced to discharge the surplus. The Arade dam was no exception as can be seen in Table 9.

It is important to highlight that the total value of water discharged during the hydrological year 2000/2001, and lost into the sea, was approximately equal to the value of the extra water withdrawn from Querença-Silves aquifer system during the drought year of 2004/2005.

Also in the 1990s there were 3 years that had an excess of precipitation forcing Arade dam to discharge.

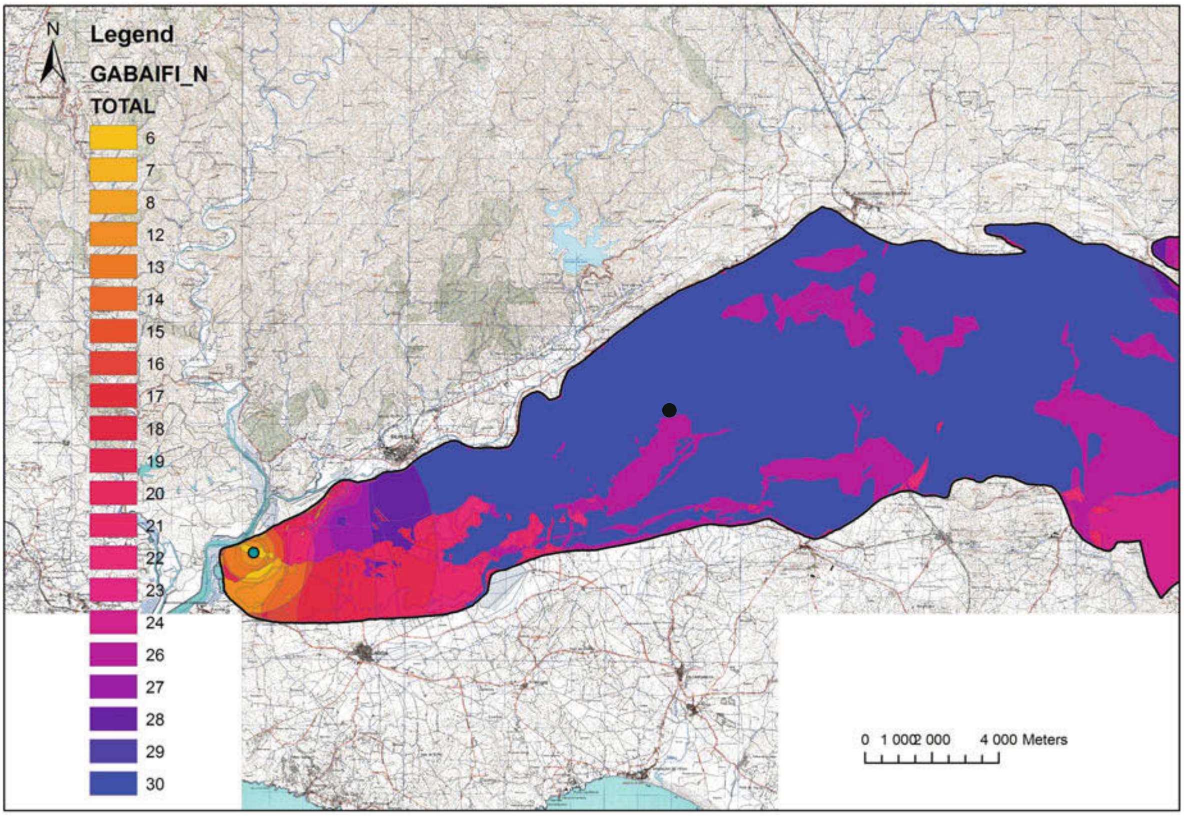

**Fig. 8** The GABA-IFI_N sub-index applied to the west of the Querença-Silves aquifer system

**Table 9** Peak discharge of the Arade dam in the hydrological year 2000/2001

| Dam | Hydrological year | Depth discharge ($10^3$ $m^3$) | Surface discharge ($10^3$ $m^3$) | Total discharge ($10^3$ $m^3$) |
|---|---|---|---|---|
| ARADE | 2000/2001 | 37,499.20 | 19,256.70 | 56,755.90 |

**Table 10** Peak discharge volume of the Arade dam in the hydrological years of 1995/1996, 1996/1997 and 1997/1998 (obtained in http://snirg.inag.pt)

| Dam | Hydrological year | Depth discharge ($10^3$ $m^3$) | Surface discharge ($10^3$ $m^3$) | Total discharge ($10^3$ $m^3$) |
|---|---|---|---|---|
| ARADE | 1995/1996 | 0 | 81, 255.39 | 81, 255.39 |
| | 1996/1997 | 0 | 42, 599.62 | 42, 599.62 |
| | 1997/1998 | 8.556,65 | 113, 762.30 | 122, 318.97 |
| | | | Total ($\times 10^3$ $m^3$) | 246, 173.98 |

From the hydrological year 1995/1996 to the year 1997/1998 the dam discharged a volume of 250 $hm^3$ of water (cf. Table 10).

All this water was "lost" into the sea and could have been used for artificial recharge.

Eventually, we may notice in the future a more acute need to use non-conventional water resources. According to recent climate change reports, this succession of "wet years–dry years" is going to happen more often.

Regarding the quality of the water source, several studies and reports point out that eventually Funcho dam and Arade dam will have water quality problems from upstream agriculture fields. Fortunately by fulfilling the objectives of the Water Framework Directive that has to be rectified before the year 2015, when all European water bodies must have attained a "good quality" status.

So the next question will be, having available water, how can we inject it underground? This is the topic of the next section.

## Artificial Recharge Experiments in the Algarve

### Introduction

As mentioned in the Introduction, the main objectives of the GABARDINE Project in the Algarve were (1) to identify alternative water sources and study the economic and environmental feasibility of its use in semi-arid areas, in the context of an integrated water resources management; (2) to study the aquifers as a main water source for both seasonal and long-term storage of these alternative water sources; and (3) to improve knowledge about possible methods to introduce these water sources in the aquifer, namely through artificial recharge.

Alternative water sources for groundwater artificial recharge may include superficial runoff surplus produced during flash flood events, treated urban wastewater, desalinated water surplus or water import.

The development of this study approached several issues related to the subject like precipitation rate analysis, both water and recharge balance, identification of the potential alternative water sources intended to recharge the aquifer and assessment of existing technologies for its use, development of tools aimed for managing groundwater resources considering artificial recharge, assessment of aquifer vulnerability and characterization of the unsaturated zone. Several artificial recharge devices have been developed and implemented in the GABARDINE Project.

Regarding the Campina de Faro case study in the Algarve, not far from the Querença-Silves aquifer previously described, the main goal was to optimize groundwater rehabilitation through the implementation of artificial recharge, minimizing the effects of diffuse pollution caused by agricultural practices. This goal aimed at the assessment in the Portuguese study area of problems resulting from the application of these practices. Today groundwater quality has been well documented. The study area was designated as a vulnerable area concerning nitrate concentration by the application in Portugal of the Nitrate Directive (in 2004). Together with the "good quality status" referred by the Water Framework Directive, these are the main reasons for the implementation of infrastructures aimed at the improvement of groundwater quality in a section of this aquifer allowing, on the other hand, increasing groundwater availability with good quality in the Algarve region.

The project improved scientific knowledge on several methodologies aimed not only to improve groundwater quality but also at allowing subterranean storage of water with good quality in wet year periods of major availability and during events of heavy rainfall.

GABA-IFI method, presented before, aims at preliminary identification of candidate areas for the installation of groundwater artificial recharge systems. Besides the application to the Querença-Silves aquifer, this new method was also applied to Campina de Faro aquifer.

Several artificial recharge experiments were accomplished in the Portuguese case study area during the second year of the project by Diamantino et al. (2007). Figure 9, presenting a set of selected pictures, shows examples. The purpose of the experiments was to assess and quantify the effectiveness and applicability of the different groundwater artificial recharge methodologies, in a way that the achieved results could contribute to the development of the GABARDINE Decision Support System (GDSS).

Complementarily, a preliminary development of an optimization model that merges restrictions and parameters for the objective function was addressed. Its future application will allow selecting more adequate techniques considering the maximization of the improvement of water quality and total cost minimization.

### Artificial Recharge Tests in Infiltration Basins

The objective of the AR was the assessment of infiltration rates in the very permeable yellow sands and to assess the unsaturated zone and saturated zone transport parameters with a tracer test. To accomplish this purpose Areal Gordo AR Basins 1, 2 and 3 (Figs. 9 and 10) have been constructed for in situ infiltration and tracer test experiences. Besides, laboratory soil-column tests were performed in soil samples collected at the bottom of the basin. Areal Gordo AR

**Fig. 9** Vertical profile of lithological materials in Areal Gordo (at *right*) and LNEC4 well lithological column and infiltration basin in the first layer (at *left*)

**Fig. 10** Infiltration basin in the second layer and monitoring equipment used for the infiltration test

Basin 2 had an area of 61 $m^2$. The bottom was excavated up to the third layer of yellow sandy soils at approximately 8 m depth. The source of water for this infiltration test comes from a nearby well opened in the confined aquifer. To fulfil the objective of measuring the infiltration rate capacity, the water level in the basin was maintained constant (with a water column of approximately 90 cm) for a period of 3 days, and the infiltration rate was calculated by dividing the volume of water added by the basin area. At that time, the piezometric level and the groundwater quality parameters were continuously recorded in LNEC4 well. The arrival time to this well was 70 h. This allowed estimating the permeability of this sandy layer as 0.21 m/day, considering the distance of 8 m between the bottom of the infiltration pond and the well (i.e. up to 1.5 m in the vadose zone + 6.5 m distance in the aquifer).

## Artificial Recharge Using a Large Diameter Well

In the case study area of Campina de Faro a large amount of 5.0 m diameter wells equipped with a waterwheel are common, the so-called noras (Fig. 11). Some of them are still used for agricultural irrigation or even domestic consumption. In Areal Gordo an injection test was performed in one of those wells with the objective of assessing if they could be effective infrastructures to be used as already available facilities for AR. Also foreseen was the assessment of the infiltration rate vs. the recharging depth of water column, ranging from the surface to water table depth. Besides recording the level inside the large diameter well the effect of the recharge in the regional water level was monitored in the nearby monitoring well. This well

**Fig. 11** Injection test developed in the “nora”: water levels at the beginning and at the end of the test

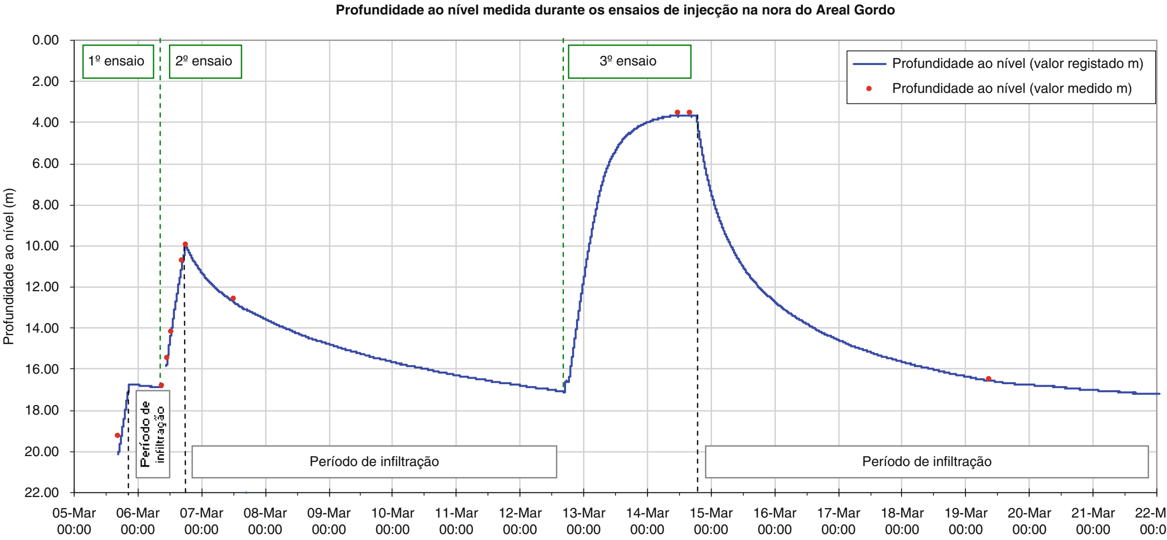

**Fig. 12** Depth to the water table automatically recorded and manually measured during the injection tests performed in the “nora”

allowed assessing a first approach to the groundwater hydraulic conductivity and some transport parameters. The input water discharge from a close deep well was controlled during the injection periods. The main characteristics of this large diameter well are presented hereinafter: area at the bottom of the “nora” with a diameter of 5 m = 19.625 m; depth to water table at the beginning of the first test = 19 m; available storage volume at the “nora” for the test = 373 $m^3$; total well depth = 24 m. The monitoring equipment used was the following: multiparametric water sensors for continuous monitoring installed in the “nora” and LNEC5 well; from the discharge well a flow meter was installed for continuously recording the discharge water volume.

Three injection tests were developed during March 2007. A maximum value was assessed when the water level at the “nora” stabilized near the surface (at 1.5 m depth) allowing the recharge water input of 20 $m^3$/h to be incorporated in the aquifer. The values vary with the water level inside the “nora” ranging from 0.25 m/day to 1.18 m/day to a maximum value of 24.5 m/day, respectively, for the 1st, 2nd and 3rd test (Fig. 12). As expected, it was concluded that increments in the infiltration rate are strongly connected to the increase in the water column inside the well.

## Artificial Recharge Using a Medium Diameter Well

A 1 day injection test was performed in an experimental medium diameter well of 0.5 m, located in Areal Gordo, and called LNEC6. The objective of this test was to determine the infiltration capacity and to compare it to the one assessed for the 5 m large diameter

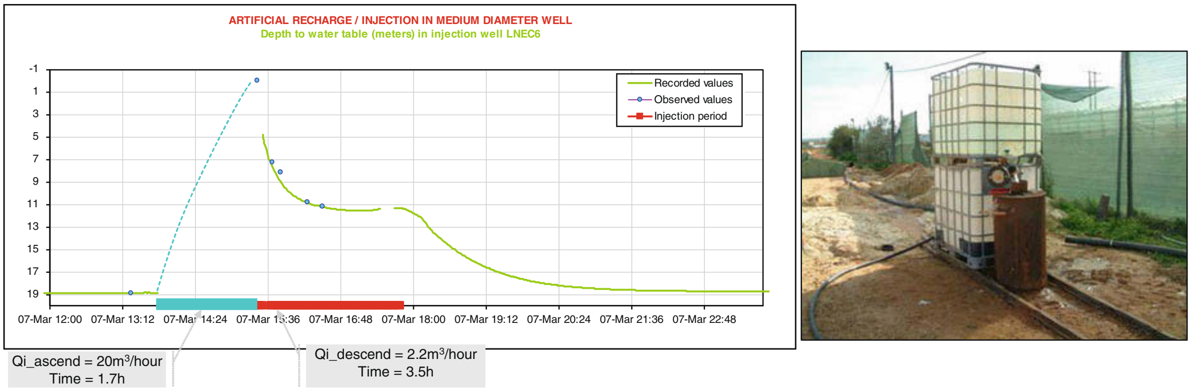

**Fig. 13** Depth to the water table automatically recorded and manually measured in LNEC6 (medium diameter well) during the injection test

"nora". The injection test was performed for 4 h and the depth to water table was recorded during the test. The input water discharge from a close deep well was controlled during the injection periods. Two injection discharges were considered, one to fill up the well and the other necessary to stabilize the water level: Qi_ascend = 20 $m^3$/h and Qi_descend = 2.2 $m^3$/h. The main characteristics of LNEC6 well, opened in the unconfined sandy aquifer, are the following: section area (diameter 0.5 m) = 0.196 $m^2$; depth to water table = 18.9 m; available storage volume = 3.7 $m^3$; total well depth = 28 m. The monitoring equipment used was the same as in the previous injection test. The depth to the water table recorded in LNEC6 is plotted in Fig. 13 as well as the two injection periods (4 h total time duration). The infiltration rate was calculated by the change in the water level after the stop of injection and during the necessary time interval to achieve the initial head, before the injection test (i.e. 7.4 m of water level variation during 0.6 days = 11.5 m/day of infiltration rate).

## Artificial Recharge Experiments in River Bed Infiltration Basins

In the Rio Seco river bed, two 100 $m^2$ (20 m (H) × 5 m (W) × 5 m (D)) infiltration basins were constructed and filled in with clean gravels for AR tests (Fig. 14). The main objectives of the experiment were

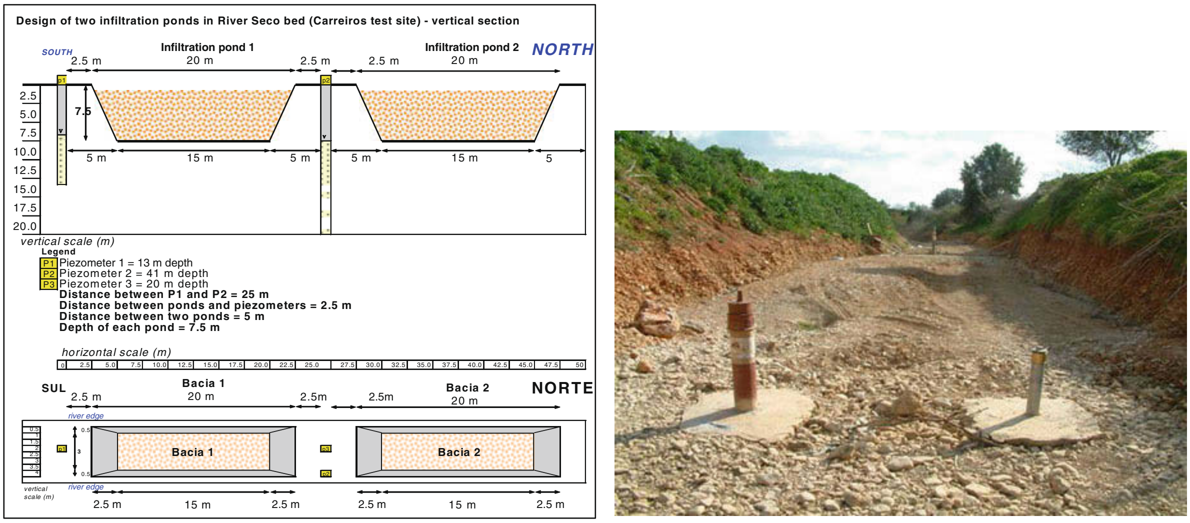

**Fig. 14** Design configuration of the two infiltration basins in the river bed of Rio Seco (Carreiros)

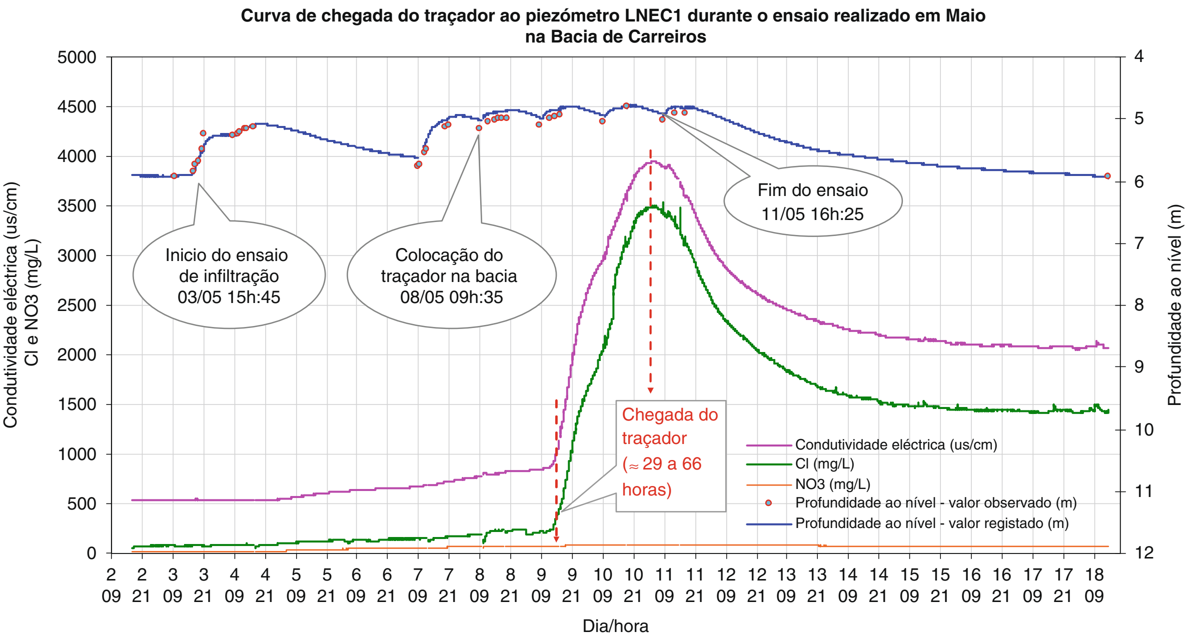

**Fig. 15** Breakthrough tracer experiment curves at Rio Seco infiltration basin (Carreiros)

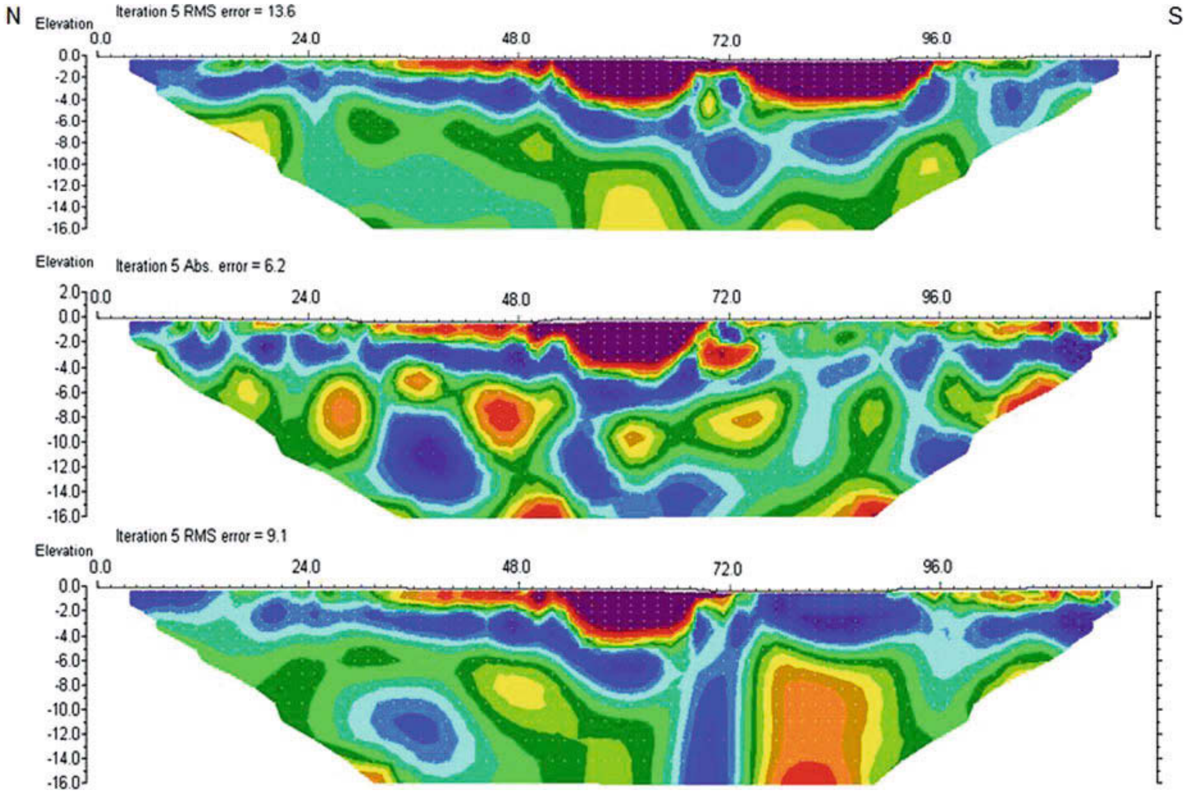

**Fig. 16** Electrical resistivity models obtained before, during and after the tracer test at the infiltration basin in Rio Seco, Carreiros (Mota et al., 2008)

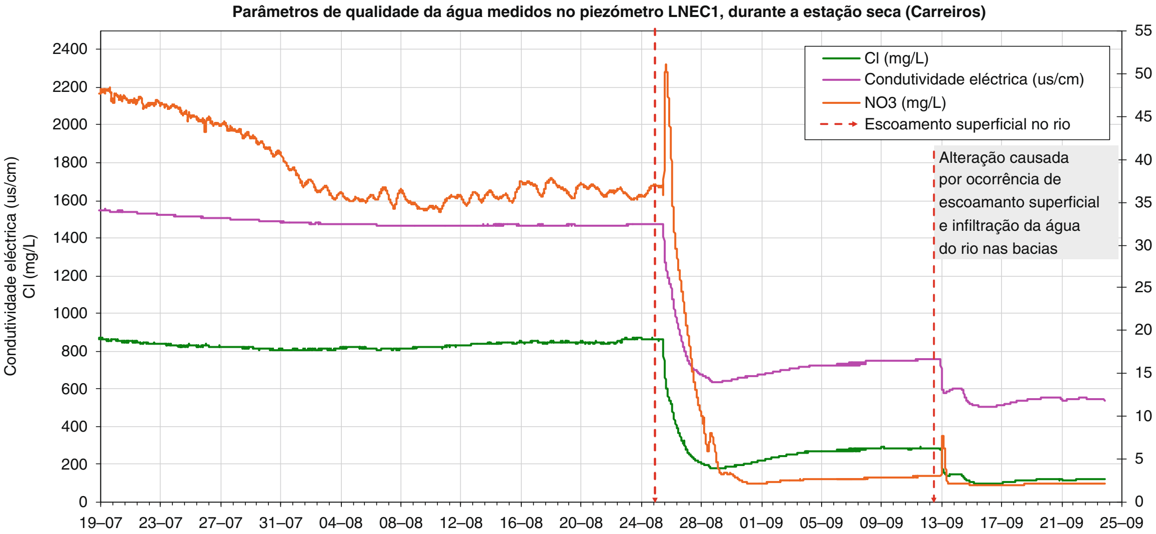

**Fig. 17** Variation of the water quality in Campina de Faro unconfined aquifer, after runoff events in Rio Seco, monitored in LNEC 1 piezometer 2.5 m downstream of the infiltration basin

to assess the effectiveness of this type of AR structures for surface water infiltration, including the computation of groundwater recharges rates and evaluating groundwater mass transport parameters in unconfined aquifer via the monitoring of a breakthrough tracer curve. Two concrete sections were constructed and two pneumatic gauges for river water level control were installed, upstream and downstream of the infiltration basins, during January 2007, in order to measure the river discharge upstream and downstream the AR infiltration basins. Tracer tests have been performed during May 2007 (Figs. 15 and 16).

Results of the groundwater quality and quantity assessment recorded in the monitoring wells during the rainy months of November and December 2006, when surface runoff infiltrates in basins, show $NO^{3-}$ concentrations strongly decreasing the same period, tending to get closer to the $NO^{3-}$ quality value of the river water (Fig. 17).

This is a remarkable fact and of paramount relevance regarding the achievements of artificial recharge experiments towards the rehabilitation of the polluted unconfined aquifer, confirmed by LNEC 1 piezometer 2.5 m downstream of the infiltration basin.

## Conclusions

As the main conclusion, we may state that artificial recharge may be seen as one good solution aiming at a scientific-based adaptation to climate change and/or climate variability conditions in the near future. This technology allows the use of surplus water in wet years, so that extra supply water may be available later in dry years. As we have clearly shown in this chapter for Campina de Faro, other uses can be aimed for artificial recharge facilities, e.g. for cleaning polluted aquifers. So, the solutions proposed are worthy to be considered in implementing integrated water resource management plans, being part of a variety of solutions to minimize the water scarcity, for instance in the Algarve during severe drought situations.

Several in situ artificial recharge experiments and laboratory tests were performed in the framework of the GABARDINE Project for a selected area of the Campina de Faro aquifer system. The comparison of different lithologic materials in situ and in the lab and the assessment of artificial recharge efficiency allowed data gathering regarding performances (on rates of infiltrations) and the adequacies of the different techniques for different geological layers (Fig. 18). The in situ experiences showed very favourable rates of infiltration in yellow sands, especially in the large diameter well (“nora”) experiment, when infiltration rates were as high as 24 m/day. In the case of the “nora” a function of the infiltration rate vs. the water column depth in the “nora” was computed.

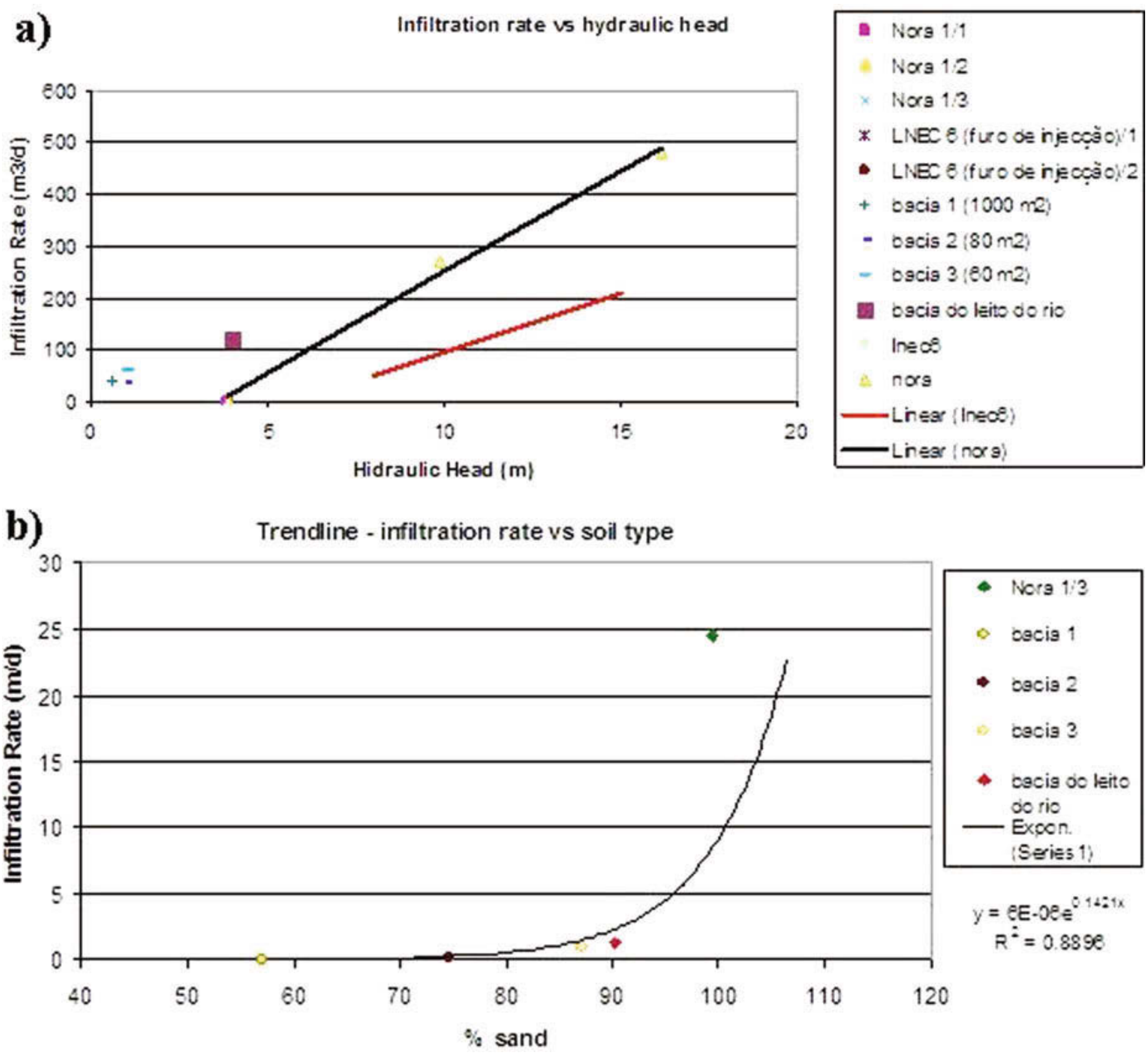

**Fig. 18** (**a**) Infiltration rates vs. the type of technology used (infiltration basins in the field or in river bed and large and medium diameter recharge wells). (**b**) Infiltration rates vs. the type of soil available in the Algarve at Campina de Faro and Rio Seco

The aim of all these experiments was to improve the knowledge on real case studies that involve application of different AR methodologies to assess the parameters needed to develop optimization models. The model may incorporate restrictions and parameters of the objective function with the values evaluated in the experiments described above. The results presented in this chapter allow the selection of the most appropriate AR techniques aiming at the maximization of groundwater storage and/or quality improvement, while minimizing costs.

**Acknowledgements** This chapter is based on the 6th Framework Programme, Project GABARDINE – "Groundwater artificial recharge based on alternative sources of water: advanced integrated technologies and management". LNEC Applied Research Programme 2005–2008 (Project P3: Groundwater resources assessment and numeric modelling in hydrogeology; Study E11: Groundwater artificial recharge, GABARDINE Project). The Portuguese Fundação para a Ciência e a Tecnologia (FCT) co-financed Ms Catarina Diamantino Ph.D. at LNEC. The dissertation was completed and delivered to Lisbon University, February 2009.

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# Groundwater in the 21st Century – Meeting the Challenges

Kevin M. Hiscock

**Abstract**

Groundwater is an important natural resource and an essential part of the hydrologic cycle. Worldwide, it has been estimated that more than 2 billion people depend on groundwater for their daily water supply. A large proportion of the world's irrigated agriculture is dependent on groundwater, as are a large number of industries, and groundwater is also critical in sustaining streams, lakes and wetland ecosystems. In many countries, excessive groundwater development, encroachment on recharge areas, uncontrolled urban and industrial discharges, contamination by naturally occurring chemicals and agricultural intensification have compromised the ability of groundwater to help resolve the emerging water management crisis in the 21st century. Side effects include escalating pumping costs, land subsidence, land degradation, reduced recharge, loss of flow to ecologically important wetlands and the intrusion of aquifers by saline water from estuaries and seas. Against this background there is an urgent and ongoing need to address the governance and practical management of groundwater resources. Over recent decades, scientific advances have created a solid platform of technical knowledge, but this has yet to strongly influence public policy, management institutions and decision making. Thus, there is an urgent need for new strategies for groundwater governance, incorporating the most advanced knowledge and data, in order to maintain the availability of high-quality groundwater resources to meet human, economic and ecosystem needs.

**Keywords**

Groundwater resources • Transboundary aquifers • Groundwater contamination • Climate change • Ecosystem services • Adaptive management

## Introduction

The vast store of water beneath the ground surface has long been realised as an invaluable source of water for human consumption and use. Groundwater development dates from ancient times, as demonstrated by the wells and horizontal tunnels known as qanats

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(ghanats) or aflaj: small, artificial channels excavated as part of a water distribution system that originated in Persia about 3000 years ago and are found in a band across the arid regions extending from Afghanistan to Morocco. In more recent times, the location of groundwater resources has been crucial in the economic development of rural and agricultural areas such as the Great Artesian Basin aquifer in the outback of Australia (Prescott and Habermehl, 2008) and the High Plains aquifer in the mid-section of the United States (Dennehy et al., 2002), and also urban and industrial areas such as the Cretaceous Chalk aquifer underlying the London Basin (Price, 2002) and the Quaternary alluvial aquifer of the North China Plain (Foster et al., 2004).

Unfortunately because it is unnoticed underground, groundwater is often unacknowledged and undervalued resulting in adverse environmental, economic and social consequences. The over-exploitation of groundwater by uncontrolled pumping can cause detrimental effects on neighbouring boreholes and wells, land subsidence, saline water intrusion and the drying out of surface waters and wetlands. Without proper consideration for groundwater resources, groundwater pollution from uncontrolled use of chemicals and the careless disposal of wastes on land cause serious impacts requiring difficult and expensive remediation over long periods of time. Achieving sustainable development of groundwater resources by the future avoidance of over-exploitation and contamination is a major challenge for the 21st century. This chapter aims to highlight these challenges and to provide an assessment of actions needed now to protect groundwater from further uncontrolled development and degradation in the face of future environmental and climate change.

## Challenges of Groundwater Resources Development

Total global freshwater use is estimated at about 4000 km$^3$/year (Margat and Andréassian, 2008) with 99% of the irrigation, domestic, industrial and energy use met by abstractions from renewable sources, either surface water or groundwater (Fig. 1 and Table 1). Less than 1% (currently estimated at 30 km$^3$/year)

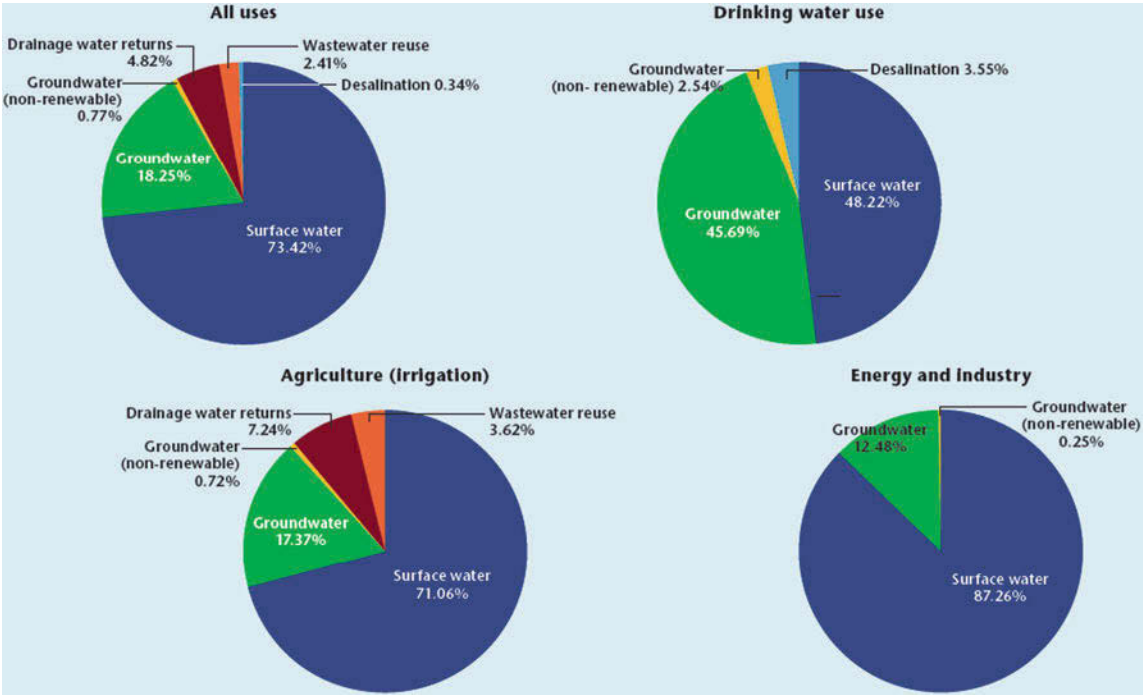


**Fig. 1** Sources of water use globally and for major sectors, 2000. After FAO-AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm) and WWAP (2009)

**Table 1** World water resources and abstractions for 2000 in km$^3$/year (unless otherwise indicated). After IWMI (2007) and WWAP (2009)

| Region | Renewable water resources | Total water abstractions | Water abstractions | | | | | | Abstractions as a percentage of renewable resources |
|---|---|---|---|---|---|---|---|---|---|
| | | | Agriculture | | Industry | | Domestic | | |
| | | | Amount | Percentage | Amount | Percentage | Amount | Percentage | |
| Africa | 3936 | 217 | 186 | 86 | 9 | 4 | 22 | 10 | 5.5 |
| Asia | 11,594 | 2378 | 1936 | 81 | 270 | 11 | 172 | 7 | 20.5 |
| Latin America | 13,477 | 252 | 178 | 71 | 26 | 10 | 47 | 19 | 1.9 |
| Caribbean | 93 | 13 | 9 | 69 | 1 | 8 | 3 | 23 | 14.0 |
| North America | 6253 | 525 | 203 | 39 | 252 | 48 | 70 | 13 | 8.4 |
| Oceania | 1703 | 26 | 18 | 73 | 3 | 12 | 5 | 19 | 1.5 |
| Europe | 6603 | 418 | 132 | 32 | 223 | 53 | 63 | 15 | 6.3 |
| **World** | **43,659** | **3829** | **2663** | **70** | **784** | **20** | **382** | **10** | **8.8** |

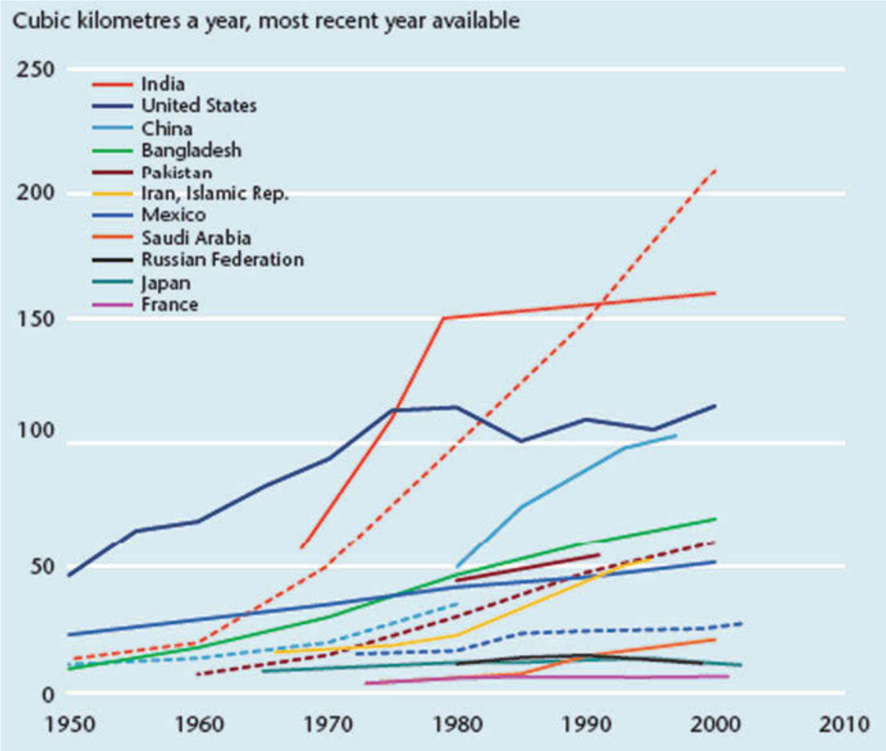


**Fig. 2** Growth in groundwater use, 1950–2000. Note that countries with two lines have different data sets that do not reconcile. After Margat (2008)

is obtained from non-renewable (fossil groundwater) sources mainly in three countries: Algeria, Libya and Saudi Arabia. With rapid population growth, groundwater abstractions have tripled over the last 50 years (Fig. 2), largely explained by the rapid increase in irrigation development stimulated by food demand in the 1970s and by the continued growth of agriculture-based economies (World Bank, 2007).

Emerging market economies such as China, India and Turkey, which still have an important rural population dependent on water supply for food production, are also experiencing rapid growth in domestic and industrial demands linked to urbanisation. Urbanised and industrial economies such as the European Union and the United States import increasing amounts of food and manufactured products, while water use in industrial processes and urban environments has been declining, due to both technological changes in production processes and pollution mitigation efforts (WWAP, 2009).

Groundwater is an important natural resource. Worldwide, more than 2 billion people depend on groundwater for their daily supply (Kemper, 2004). Aquifers, which contain 100 times the volume of freshwater that is to be found on the Earth's surface, supply approximately 20% of total water used globally, with this share rising rapidly, particularly in dry areas (IWMI, 2007). This rise has been stimulated by the development of low-cost, power-driven pumps and by individual investment for irrigation and urban uses. Globally, 65% of groundwater utilisation is devoted to irrigation, 25% to the supply of drinking water and 10% to industry. Groundwater resources account for more than 70% of the water used in the European Union and are often the only source of supply in arid and semi-arid zones (100% in Saudi Arabia and Malta, 95% in Tunisia and 75% in Morocco). Irrigation systems in many countries depend very largely on groundwater resources (90% in Libya, 89% in India, 84% in South Africa and 80% in Spain) (Zektser and Everett, 2004).

The exploitation of groundwater is largely dependent on the location of aquifers relative to the point of demand. A large urban population with a high demand for water would only be able to exploit groundwater if the aquifer, typically a sedimentary rock, has favourable storage and transmission properties, whereas in a sparsely populated rural district more limited but essential water supplies might be found in poor aquifers, such as weathered basement rock. Irrigated agriculture is the principal user of groundwater from the major sedimentary aquifers of the Middle East, North Africa, North America and the Asian alluvial plains of Punjab and Terai (Fig. 3). Less evident is the conjunctive use associated with the concentration of irrigated agriculture and urban development in many alluvial fan and delta environments (such as those of the Chao Praya, Ganges–Brahmaputra, Godavari, Indus, Krishna, Mekong, Narmada, Nile, Mississippi, Po, Yangtze and Yellow Rivers) (WWAP, 2009). Although aquifer systems exist in all continents, not all of them are renewable. For example, those in North Africa and the Arabian Peninsula were

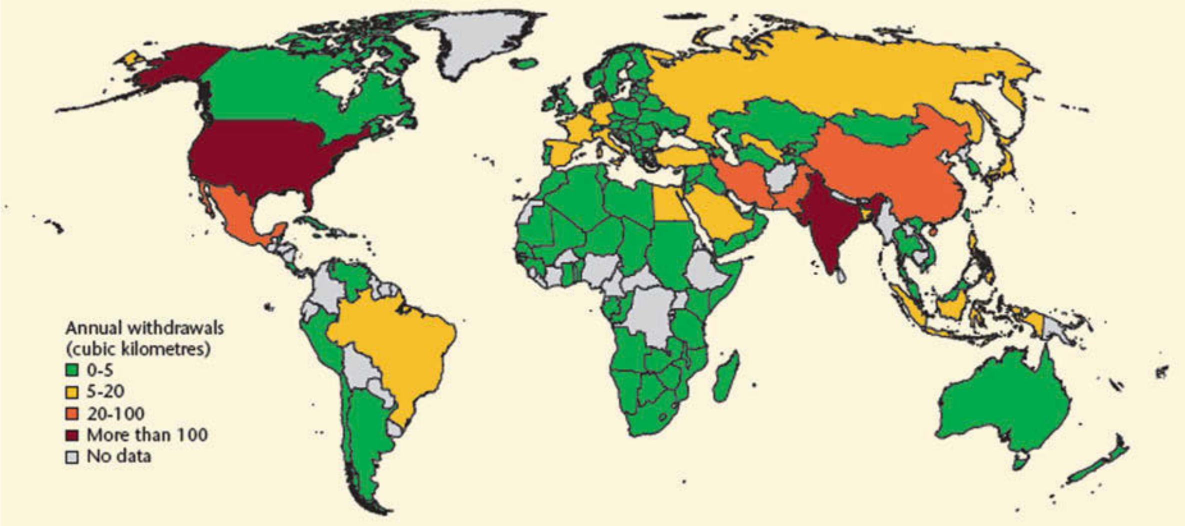


**Fig. 3** Annual abstractions (withdrawals) of renewable groundwater sources on a national basis, 1995–2004, most recent year available. Note that national averages can mask the true situation, which can vary greatly on a local scale. After Margat (2008) and WWAP (2009)

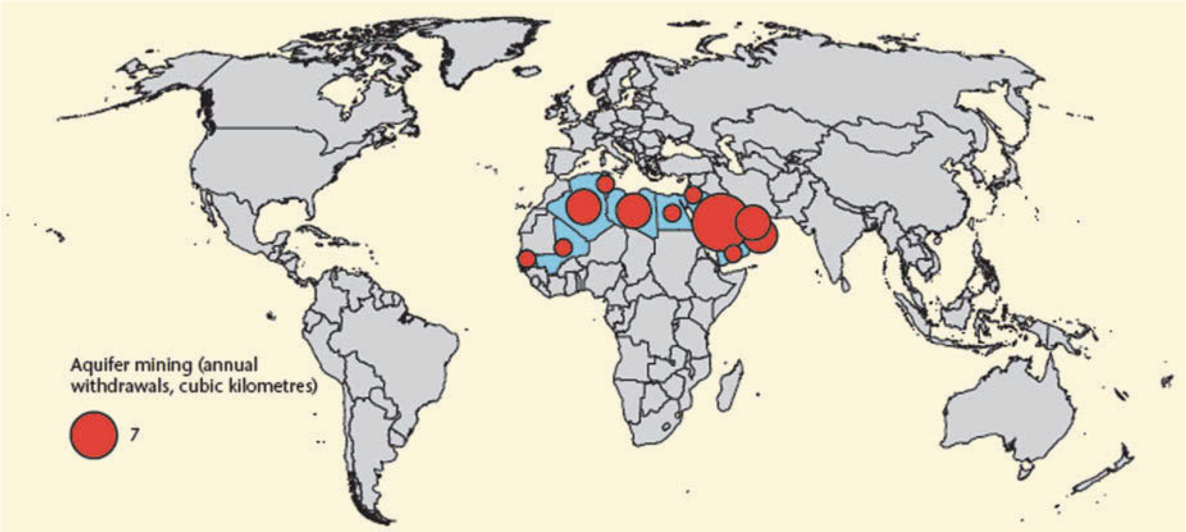


**Fig. 4** Annual abstractions (withdrawals) of non-renewable (fossil) groundwater sources in North Africa and the Middle East, 1995–2004, most recent year available. Note that national averages can mask the true situation, which can vary greatly on a local scale. After Margat (2008) and WWAP (2009)

recharged more than 10,000 years ago when the climate was more humid and are no longer replenished (Fig. 4).

## Population Growth Pressures

Population growth, economic growth, urbanisation, technological change and changing consumption patterns are the main factors that influence water use, yet there is still substantial uncertainty regarding the scale of future demands. Between 2000 and 2050 the world's population is projected to grow from 6 to 9 billion and presents considerable challenges for meeting global water demand both now and in the future. Faced with this challenge, in December 2003, the United Nations General Assembly declared the years 2005–2015 as the International Decade for Action, 'Water for Life', in support of the Millennium Development Goals (MDGs) of reducing by half the proportion of people without access to safe drinking water; stopping unsustainable exploitation of water resources; aiming to develop integrated water resource management and water efficiency plans; and halving the proportion of people who do not have access to basic sanitation. Maintaining secure water supplies under the MDGs would be impossible without groundwater. Unlike other natural resources, groundwater is present throughout the world and, generally, can be abstracted year-round, indefinitely, provided that there is adequate replenishment and that the source is protected from pollution (IYPE, 2005).

## Rural Groundwater Supply and the Millennium Development Goals

Globally, there are still at least 1.1 billion people lacking access to safe drinking water. Many of these people live in rural areas and are among the poorest and most vulnerable to be found anywhere in the world. In sub-Saharan Africa, 300 million people have no access to safe water supplies, with approximately 80% living in rural areas. Therefore, significantly increasing the coverage of rural water supply in Africa is fundamental to achieving many of the MDGs. Without safe water near dwellings, the health and livelihoods of families are severely affected.

Over much of Africa, groundwater is the only realistic water supply option for meeting dispersed rural demand. Alternative water resources can be unreliable and difficult or expensive to develop: surface water is prone to contamination, often seasonal, and needs to be piped to the point of need; and rainwater harvesting is expensive and requires good rainfall throughout the year. The characteristics of groundwater that make it better suited to the more demand-responsive and participatory approaches of rural water and sanitation programmes are: resistance to drought; proximity to the point of demand; and being naturally of good quality, protected from contamination. Water supplies from groundwater also have the benefits of being developed incrementally, often accessed cheaply, and requiring a technology that is often amenable to community operation and management (MacDonald et al., 2005).

## Groundwater Use in Agriculture

Irrigation using groundwater sources has increased agricultural production by both the expansion of cultivatable area beyond that possible with just rainfed agriculture and through higher crop yields (Turner et al., 2004). With an increasing global population, demands on groundwater will continue to rise to meet agricultural demand. Mostly, pumping by farmers has been determined less by groundwater management and more by the prices of basic commodities and cash crops compared with the costs of production, including energy for pumping. Particularly in areas associated with the 'green revolution', heavy groundwater pumping has led to unsustainable conditions, with falling water levels, degraded groundwater resources and increased salinisation.

Expanding municipalities and growing light industrial and commercial activities in peri-urban and linked rural areas are increasingly competing with agriculture over groundwater quantity and quality. Even if agriculture is, within certain limits, indifferent to groundwater quality, precision agriculture is likely to be located near urban areas, and the use of high quantities of chemical fertilisers, pesticides and fungicides threatens to contaminate shallow groundwater. While relatively less toxic organic alternatives to persistent chemical compounds exist, the impacts of large-scale commercial farming near cities on what may be key strategic groundwater reserves is a key challenge requiring effective measures for groundwater quality protection that require urban and agricultural land-use regulations to be considered together (WWAP, 2009).

## Groundwater Use in Urban Areas

Groundwater accounts for more than 30% of urban water supply (and a higher proportion by number of consumers) not just in megacities but also in thousands of medium-sized towns. Some cities, for example, Beijing, Dhaka, Lima, Lusaka and Mexico City, are located on or near major aquifers, and urban water utilities have drawn heavily on groundwater for their supply. In other cities, for example, Bangkok, Buenos Aires and Jakarta, the share of water derived from groundwater has fallen considerably as a result of aquifer depletion, saline intrusion or groundwater pollution. These trends have tended to obscure rapid growth over the past 10–15 years in private supplies from groundwater by residential, commercial and industrial users in Latin America and South and Southeast Asia where the scale of exploitation is generally determined by the cost of access to shallow aquifers rather than their yield.

For many heavily exploited aquifers, groundwater abstraction and use are still poorly quantified, and dedicated groundwater monitoring networks have not been established. Instead, periodic head observations are made of pumped wells, which give only an approximate measure and are completely inadequate for detecting response to recharge events. The consequences of uncontrolled development of groundwater resources and waste disposal practices in urban areas include decreases in drinking water production, subsidence due to excess pumping, and leakage and contamination of shallow aquifers from sanitation networks or waste disposal sites (WWAP, 2009).

## Groundwater Over-exploitation

The over-exploitation, or mining, of groundwater occurs when abstractions exceed the natural replenishment of aquifers by freshwater recharge and so causing an unremitting decline in water table levels. In South Asia, for example, subsidised rural electrification to meet irrigation demands has been a key driver of groundwater use, especially in dryland areas with no surface water services. The concentration of drilling, pumping and well maintenance services has progressively reduced the cost of groundwater exploitation. The flat rate electrical energy policy in parts of South Asia (and subsidised rural electricity elsewhere) is not the major cause of groundwater resource over-exploitation, but it has allowed grossly inefficient use of energy in pumping groundwater from shallow, low-storage aquifers in hard rock terrains (Shah et al., 2006).

Another effect of over-exploitation of groundwater from aquifers comprising loosely consolidated deposits is ground subsidence. The effects of rapid urbanisation and industrialisation are especially apparent in China, where increasing subsidence has led to extensive environmental and economic damage in more than 45 cities, more than 11 of which have experienced cumulative subsidence of more than 1 m. Tianjin experienced related economic losses from 1959 to 1993 estimated at US $27 billion. Shanghai took action in 1965, as total subsidence since 1920 had reached as much as 2.63 m. Pumping has been reduced by 60%, and users are requested to inject the same quantity of water into aquifers in winter as is used in summer (WWAP, 2009).

## Groundwater Depletion in North East India

The World Bank has warned that India is on the brink of a severe water crisis (Briscoe, 2005) with groundwater abstractions as a percentage of recharge as much as 100% in some states (Fig. 5). Nationally, groundwater accounts for about 50–80% of domestic water use and 45–50% of irrigation (Kumar et al., 2005; Mall et al., 2006). The total irrigated area in India nearly tripled to 33,100,000 ha between 1970 and 1999 (Zaisheng et al., 2006). The states of Rajasthan, Punjab and Haryana in North West India are semi-arid to arid, averaging about 50 cm of annual rainfall (Xie and Arkin, 1997), and encompass the eastern part of the Thar Desert. The 114,000,000 residents of the region have benefitted from India's 'green revolution', a massive agricultural expansion made possible largely by increased production of groundwater for irrigation, which began in the 1960s. Wheat, rice and barley are the major crops. The region is underlain by the Indus River plain aquifer, a 560,000 km$^2$ unconfined to semi-confined porous alluvial formation that straddles the border between India and Pakistan (Zaisheng et al., 2006).

In a study using terrestrial water storage change observations from the NASA Gravity Recovery and Climate Experiment (GRACE) satellites, Rodell et al. (2009) simulated soil water variations from a data integrating hydrological modelling system to show that groundwater is being depleted at a mean rate of 4.0 ± 1.0 cm/year equivalent height of water (17.7 ± 4.5 km$^3$/year) over the Indian states of Rajasthan, Punjab and Haryana (including Delhi), with maximum rates of groundwater depletion centred on Haryana. Assuming a specific yield of 0.12, the regional mean rate of water table decline is estimated to be about 0.33 m/year. Local rates of water table decline, which are highly variable, are reported to be as large as 10 m/year in certain urban areas.

During the period August 2002 to October 2008, a period when annual rainfall was close to normal, groundwater depletion was equivalent to a net loss of

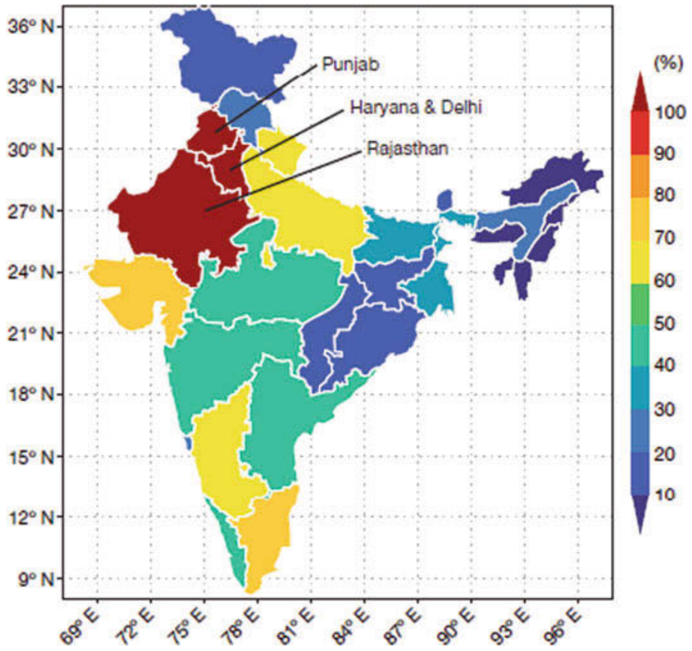


**Fig. 5** Groundwater abstractions as a percentage of recharge. The map is based on state-level estimates of annual abstractions and recharge reported by the Indian Ministry of Water Resources (2006). After Rodell et al. (2009)

109 km$^3$ of water, about double the capacity of India's largest surface water reservoir. Although the GRACE observational record is relatively short, the results suggest that unsustainable consumption of groundwater for irrigation and other anthropogenic uses is likely to be the cause. If measures are not taken soon to ensure sustainable groundwater usage, the consequences for the population of the region may include a reduction of agricultural output and shortages of drinking water, leading to extensive socio-economic stresses (Rodell et al., 2009).

## Transboundary Aquifers

Key features of transboundary aquifers include a natural subsurface path of groundwater flow, intersected by an international boundary, such that water transfers from one side of the boundary to the other (Fig. 6). In many cases the aquifer might receive the majority of its recharge on one side and the majority of its discharge on the other. The subsurface flow system at the international boundary itself can be visualised to include regional, as well as the local movement of water. In hydrogeological terms, these shared resources can only be estimated through good observations and measurements of selected hydrologic parameters, such as precipitation, groundwater levels, stream flow, evaporation and water use. A monitoring programme should aim to provide the data essential to generate a conceptual and quantitative understanding of the status of a transboundary aquifer system.

Since the year 2000, UNESCO's International Hydrological Programme has been participating in the establishment of a groundwater database and the presentation of a detailed map of transboundary aquifers. So far, the inventory comprises 273 shared aquifers: 68 are on the American continent, 38 in Africa, 65 in eastern Europe, 90 in western Europe and 12 in Asia. Transboundary river basins cover 45% of the Earth's land area, affect 40% of the world's population and account for 60% of global river flows (UNESCO, 2008).

Water ignores political and administrative boundaries, evades institutional classification and eludes legislative generalisations such that international water law has a limited record in resolving transboundary water issues. Of the transboundary aquifers in Europe, many remain unrecognised by one of the sharing countries. The aquifers in Africa, however, which are some of the biggest in the world, are still largely under-exploited. These aquifers have considerable potential,

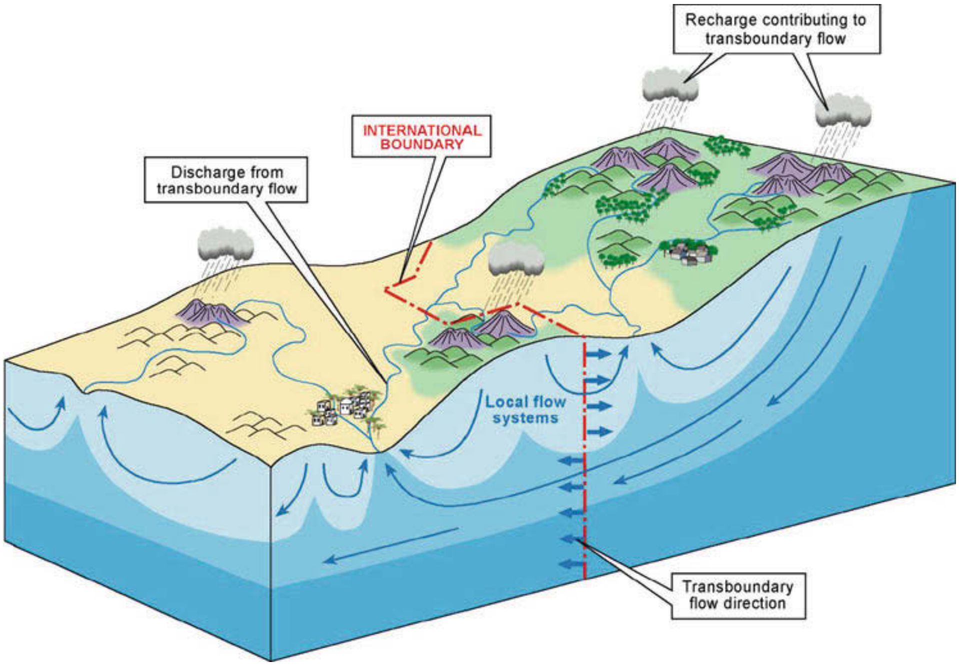


**Fig. 6** Schematic illustration of a transboundary aquifer. After Puri et al. (2001)

provided that their resources are managed on a sustainable basis. Since they generally extend across several state boundaries, their exploitation will require agreed management mechanisms in order, for example, to prevent pollution or over-exploitation by particular states (UNESCO, 2003).

Political tensions can be exacerbated over access to groundwater and unequal rights of use of vital aquifers can potentially lead to conflict (Bergkamp and Cross, 2006). Transboundary groundwater problems in the Middle East are an example of the socio-political impacts of groundwater depletion. Amery and Wolf (2004) discussed the importance of water resources in peace negotiations. For example, boundaries with Syria were based on precedent and international law together with hydro-strategic needs. In the case of Israel and Palestine, the coastal plain aquifer extends from Carmel (near Haifa) in the north to the Palestinian Gaza Strip in the south. According to Kandel (2003), serious conflict exists between Israel and Palestine over this aquifer, which is both directly and indirectly related to the conflict over land.

## The Transboundary Guaraní Aquifer System

The Guaraní Aquifer System underlies areas of Brazil, Uruguay, Paraguay and Argentina (Fig. 7) and outcrops in dense populated areas such as São Paulo state in Brazil. The aquifer contains water of very good quality and is exploited for urban, industrial and irrigation supplies and for thermal, mineral and tourist purposes. This aquifer system is one of the most important underground freshwater reservoirs in the world covering an area of about 1,200,000 km$^2$ with a volume of 40,000 km$^3$, enough storage volume to supply a global population of 5500 million people for 200 years at a rate of 100 l/day/person. This enormous aquifer is located in the Paraná and Chaco-Paraná Basins of southern South America. It is contained in aeolian and fluvial sands of Triassic–Jurassic age and is normally covered and confined by thick basalt flows (Serra Geral Formation) of Cretaceous age. The thickness of the aquifer ranges from a few metres to 800 m (Fili et al., 1998; Araújo et al., 1999).

The future exploitation of groundwater resources reliant on the Guaraní Aquifer System, which is seen as essential to the economic growth of the Mercosur region, partly depends on the development of numerical models to introduce improvements in conceptual model understanding of the aquifer and to better identify knowledge uncertainties. At present, no national or international guidelines exist which could help guarantee the sustainable management of this transboundary aquifer. Therefore, there is a need for consistent data collection and modelling to produce a database for sharing by all stakeholders of the aquifer. To this end, a Consejo Superior drawn from the member countries with a direct interest in the aquifer system has been established to coordinate a work programme studying the groundwater resources (Puri et al., 2001).

## Groundwater and Ecosystem Services

The Millennium Ecosystem Assessment report (MEA, 2005) concluded that many of the Earth's ecosystem services are seriously affected by over-use and abstraction of resources by societies. Ecosystem services are defined as the goods (food, fuel and water) and benefits (regulation of climate, flood and erosion control, soil formation, nutrient cycling, maintenance of biodiversity and recreational opportunities) provided to people by ecosystems (MEA, 2005). The MEA study concluded that freshwater-dependent ecosystems are particularly affected through over-abstraction of water resources, infrastructure development on river courses and drainage and conversion of wetlands to arable lands. Many ecosystem services have a direct linkage with groundwater storage, recharge and discharge. Rainwater flows through ecosystems to recharge aquifers and the type of ecosystem and its configuration often determine the rate and quality of the recharge. On the other hand, groundwater discharge and exfiltration of groundwater often support particular ecosystems of high value in terms of both their services and their biodiversity (Bergkamp and Cross, 2006).

Ecosystems that depend on groundwater include terrestrial vegetation, river base flow systems, aquifer and cave ecosystems, wetlands, terrestrial fauna, and estuarine and near-shore ecosystems (SKM, 2001). Groundwater-associated ecosystem services provide support to a wide range of production and consumption processes, which have high economic value (Emerton and Bos, 2004). These ecosystems depend on several

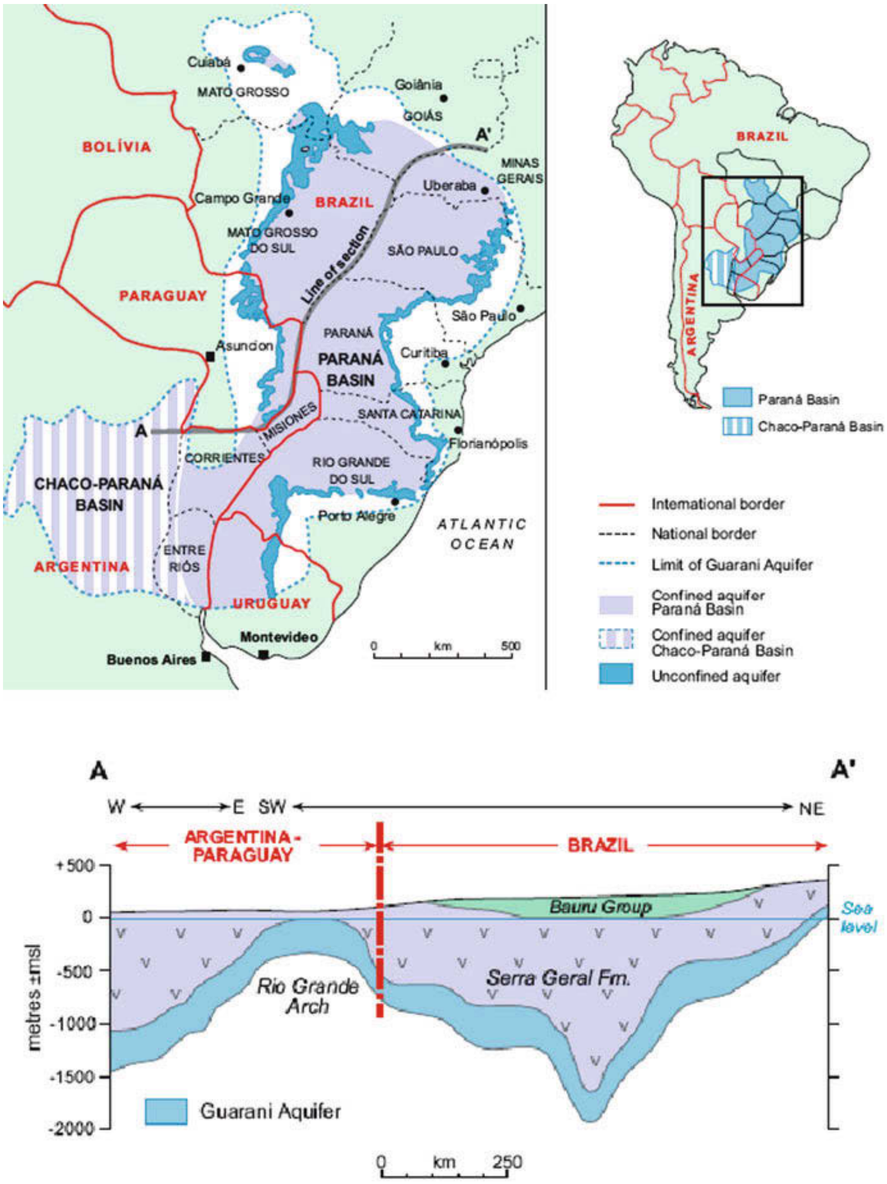


**Fig. 7** Map of outcrop and cross-section of the Guaraní Aquifer System. After Campos (2000) and Puri et al. (2001)

groundwater characteristics, which include the quality of water, discharge flux from an aquifer and the groundwater level (SKM, 2001), and small changes can potentially cause extensive damage to dependent ecosystems.

The interdependencies between ecosystem services and groundwater are little recognised and valued in decision making and management of water resources and river basins and are often taken for granted by their users. For example, although the abstraction of groundwater has generated benefits, its over-exploitation has led to the degradation of highly valued ecosystem services such as loss of fish, fuel wood and spring waters. Furthermore, groundwater extraction may harm rare and endangered species restricted to very local habitats. For example, the Edwards Aquifer-Comal Springs ecosystem provides critical habitat for the Texas blind salamander as well as 91 species and subspecies of fish that are endemic in this underground ecosystem (NRC, 2004). Currently, the challenge is to improve the understanding and awareness of the linkages between groundwater and ecosystem services and incorporate this into decision making and management (Bergkamp and Cross, 2006).

## Submarine Groundwater Discharge to Biscayne Bay, Florida

Biscayne Bay is a coastal barrier island lagoon that relies on significant quantities of freshwater to sustain its estuarine ecosystem. During the 20th century, field observations have suggested that Biscayne Bay changed from a system largely controlled by widespread and continuous submarine groundwater discharge (SGD) from the highly permeable Pliocene–Pleistocene limestone aquifer (Biscayne Aquifer) and overland sheet flow, to one controlled by episodic discharge of surface water at the mouths of canals (Langevin 2003). Kohout and Kolipinski (1967) demonstrated the ecological importance of SGD by showing that near-shore biological zonation in the shallow Biscayne Bay estuary was directly related to upward seepage of fresh groundwater (Fig. 8).

Throughout much of the area of southeastern Florida, a complex network of levees, canals and control structures is used to manage water resources. Beginning in the early 1900s, canals were constructed to lower the water table, increase the available land for agriculture and provide flood protection. By the 1950s, excessive drainage had lowered the water table by 1–3 m and caused saltwater intrusion, thus endangering the freshwater resources and dependent ecosystems of the Biscayne Aquifer. In an effort to reverse and prevent saltwater intrusion, control structures were built within the canals near Biscayne Bay to raise inland water levels. On the western side of the coastal control structures, water levels can be 1 m higher than the tidal water level east of the structures. Current ecosystem restoration efforts in southern Florida are examining alternative water management scenarios that could further change the quantity and timing of freshwater delivery to the bay. Ecosystem managers are concerned that these proposed modifications could adversely affect bay salinities (Langevin, 2003).

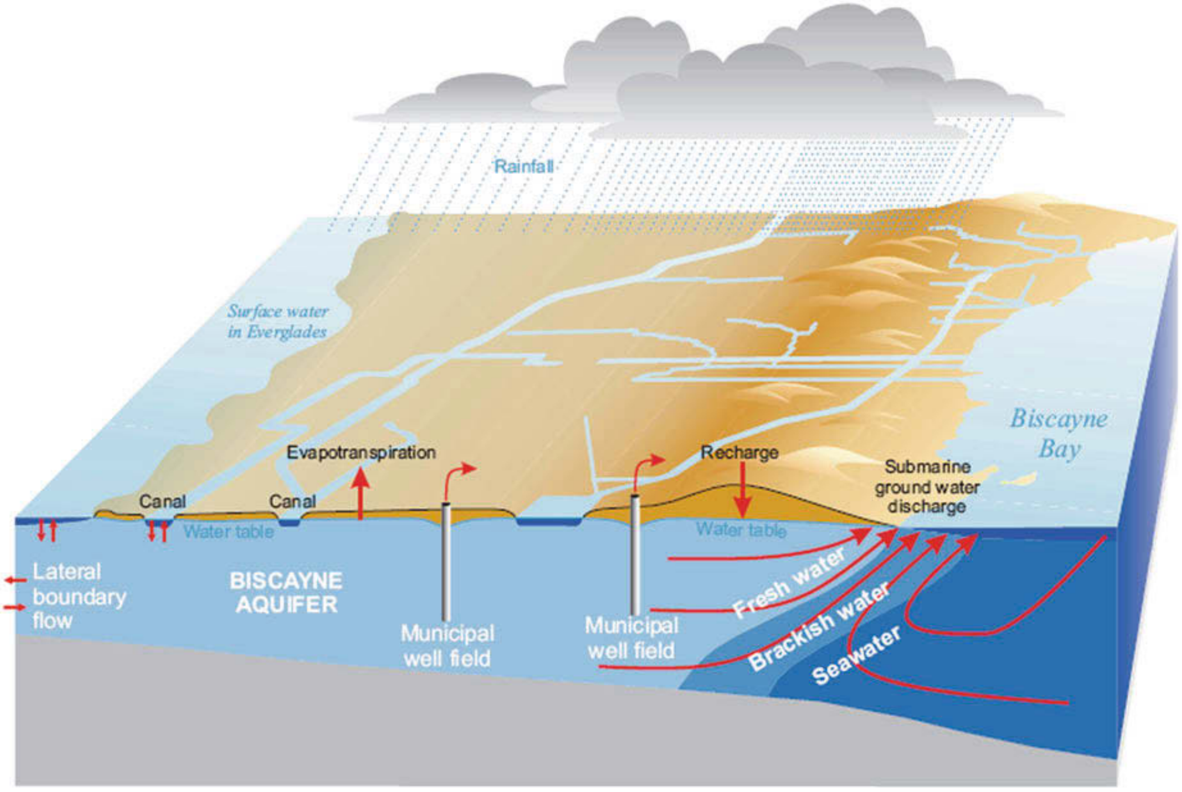


**Fig. 8** Conceptual hydrological model of submarine groundwater discharge to Biscayne Bay, Florida. After Langevin (2003)

## Groundwater Pollution and Health

The sources of groundwater contamination are many and varied (Fig. 9). In addition to natural processes, groundwater contamination is a legacy of past and present land-use practices and poor controls on waste disposal (Hiscock, 2005). Problems with groundwater quality are a consequence of pollution from both point (i.e. urban, industrial and mining activities) and non-point or diffuse sources (i.e. fertilisers and pesticides from agricultural use) (Morris et al., 2003). Soil and groundwater contamination from industrial and population expansion is of widespread concern (FAO, 2003). Pollutants that enter groundwater from agriculture, industry and urbanisation can have long-term and irreversible environmental effects. In rural areas, there has been concern over the rise in nitrate levels in many aquifers due to the heavy use of nitrogenous fertilisers in agricultural practices. Excessive nitrate from agriculture leaches through soils to stream water and groundwater, depleting soil minerals, acidifying soils and altering downstream freshwater and coastal marine ecosystems (Vitousek et al., 1997; Lake et al., 2003). Chemical spills or leaching from the surface can have a long-term environmental impact on underlying aquifers and associated ecosystem services because of the high residence time and relatively slow biodegradation rates in the subsurface (Morris et al., 2003).

The remediation of polluted groundwater can be extremely expensive. In the United States alone, NAS (1994) reported that there are an estimated 300,000–400,000 hazardous waste sites and that US $750 billion could be spent on groundwater remediation at these sites in the next few decades. In the United Kingdom, with its long industrial heritage, there are estimated to be as many as 100,000 contaminated land sites covering between 50,000 and 200,000 ha, equivalent to an area larger than Greater London (Hiscock, 2005).

## Arsenic Pollution of Groundwater in Southern Bangladesh

Environmental health impacts are another concern if poor-quality water migrates into groundwater wells

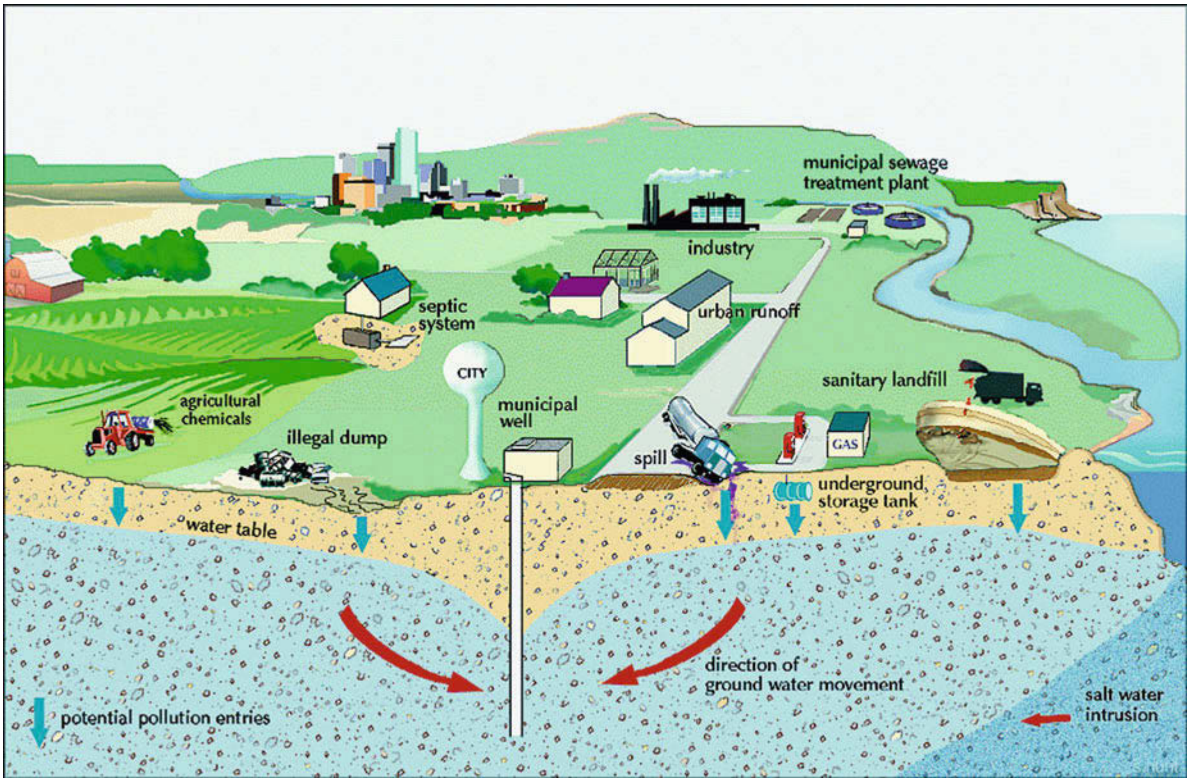


**Fig. 9** Sources of groundwater contamination. After Zaporozec and Miller (2000)

(FAO, 2003). For example, the mobilisation of naturally occurring arsenic by drilling deep tube wells in Bangladesh is directly affecting the health of some 30–35 million people. The Quaternary alluvial aquifers of Bangladesh provide drinking water for 95% of the population and also most of the water used for irrigation (Rahman and Ravenscroft, 2003). Relative to surface water, the groundwater is bacteriologically safe, and its increased exploitation since the late 1970s has probably saved many millions of lives that would otherwise have been lost to waterborne diseases resulting from the use of contaminated surface water sources. However, prolonged exposure to inorganic arsenic in water causes a variety of ailments including melanosis (a darkening of the skin), keratosis (a thickening of the skin, mostly on hands and feet), damage to internal organs and, ultimately, cancer of the skin or lungs.

Arsenic was first detected in groundwater in Bangladesh in 1993, when analysis was prompted by increasing reports of contamination and sickness in the adjoining state of West Bengal in India. The cause of the elevated arsenic concentrations in the Ganges–Meghna–Brahmaputra delta is thought to relate to the microbial reduction of arsenic-bearing iron minerals contained in the fine-grained Holocene sediments and the release of the adsorbed arsenic to groundwater (McArthur et al., 2001; Ravenscroft et al., 2001).

Groundwater studies have demonstrated the wide extent of arsenic occurrence in Bangladesh (Dhar et al., 1997; DPHE, 1999) at concentrations greater than the Bangladesh regulatory limit for arsenic in drinking water of 50 μg/L and the WHO (1994) recommended limit of 10 μg/L. These regional surveys have shown that aquifers of the Ganges, Meghna, and Brahmaputra floodplains are all affected in parts, making this the most extensive occurrence of groundwater pollution in the world (Fig. 10). It is estimated that at least 21 million people are presently drinking water containing more than 50 μg/L of arsenic, while probably more than double this number are drinking water containing more than 10 μg/L of arsenic (DPHE, 2000; Nickson et al., 2000; Burgess et al., 2002). The number of persons who must be considered 'at risk' of arsenic poisoning is even higher because testing of the 5–10 million tube wells in Bangladesh will take years to complete.

Data presented by DPHE (1999) show that the highest percentage of wells that contain arsenic concentrations above the regulatory limits of 10 and 50 μg/L occur at depths between 28 and 45 m. Hand-dug wells are mostly <5 m deep and are usually unpolluted by arsenic, but the risk of bacteriological contamination is high. Below 45 m there is a decrease in the percentage of wells that are polluted, but the risk remains significant until well depths exceed 150 m. Even so, across much of southern Bangladesh, more than 50% of boreholes in the shallow aquifer have arsenic levels that comply with the 50 μg/L limit and so continued development of the alluvial aquifers may still be possible, at least in the medium term (Burgess et al., 2002; Ravenscroft et al., 2005).

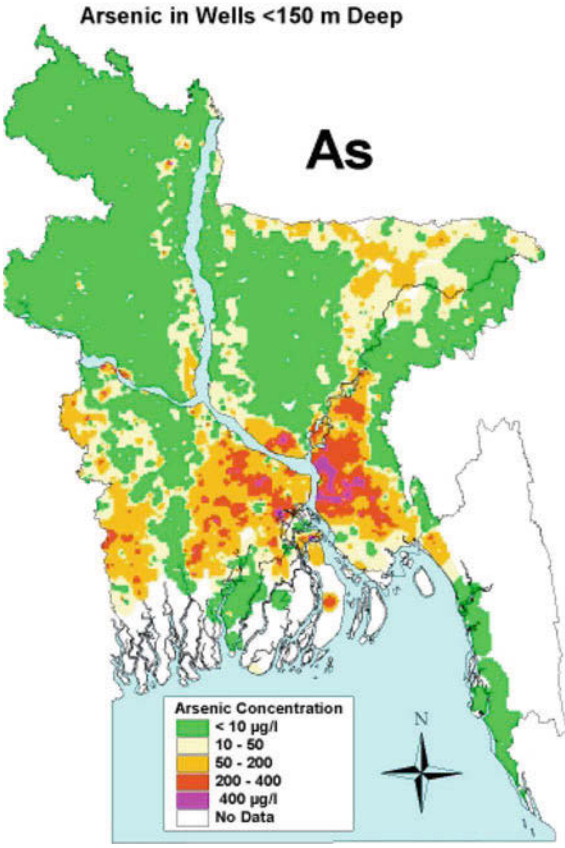


**Fig. 10** Map of Bangladesh showing the average (or most probable) arsenic concentration in the upper 150 m of the alluvial delta aquifer system. The geostatistical surface was interpolated using the ArcView Spatial Analyst® software on log-transformed data based on the surveys of DPHE (1999, 2000) which are available from http://www.bgs.ac.uk/arsenic/Bangladesh

The problem of arsenic in groundwater is not only confined to Bangladesh and West Bengal. According to Smedley and Kinniburgh (2002), areas containing high-arsenic groundwaters are well known in Argentina, Chile, China, Hungary, Mexico and Vietnam. A characteristic feature of arsenic contamination of wells in both Bangladesh and Vietnam is the large degree of spatial variability in arsenic concentrations at a local scale and, as a result, it is difficult to know when to take action to provide arsenic-free water sources. For now, it appears safer to analyse each well until further research more fully explains the sources, controls and distribution of arsenic in susceptible areas.

## Adaptation to Climate Change

The Intergovernmental Panel on Climate Change has highlighted the implications of accelerated climate change for groundwater (IPCC, 2007). Changes in rainfall, evaporation and soil moisture conditions (Fig. 11) leading to changing patterns of recharge and runoff patterns are expected to add to the resource management burden for both groundwater depletion and rising water tables, depending on the region. However, these impacts are likely to be relatively small (and possibly negligible) compared with the stresses placed on groundwater systems by current socio-economic drivers.

Climate change challenges the traditional assumption that past hydrological experience provides a good guide to future conditions (IPCC, 2007). In times of surface water shortages during droughts, groundwater resources are often abstracted as an emergency supply. Under conditions of climate change, this response is likely to be unsustainable, especially in those areas expected to experience an increase in drought

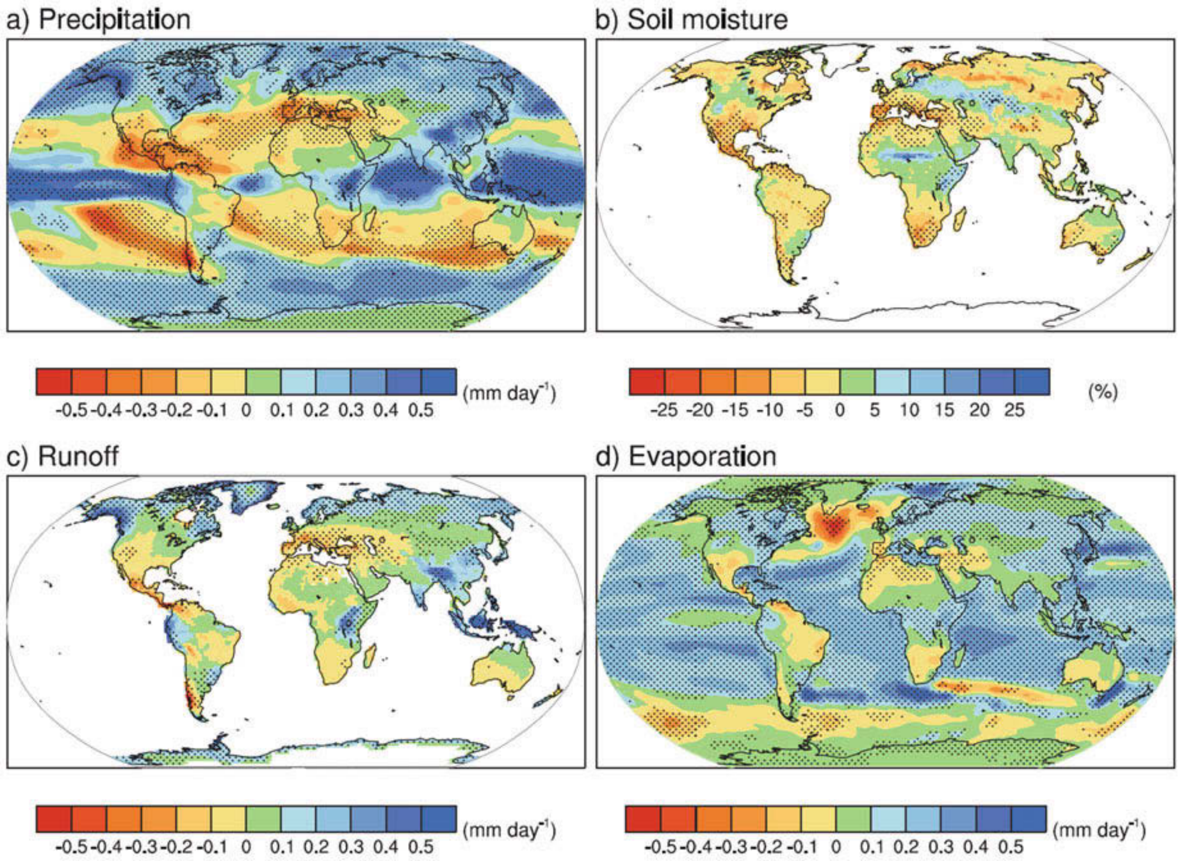


**Fig. 11** Multi-model mean changes in (**a**) precipitation (mm/day), (**b**) soil moisture content (%), (**c**) runoff (mm/day) and (**d**) evaporation (mm/day). To indicate consistency in the sign of change, regions are *stippled* where at least 80% of models agree on the sign of the mean change. Changes are annual means for the medium, A1B scenario 'greenhouse gas' emissions scenario for the period 2080–2099 relative to 1980–1999. Soil moisture and runoff changes are shown at land points with valid data from at least 10 models. After Collins et al. (2007)

frequency and duration. Also, rising sea levels under climate change will further threaten coastal freshwater aquifers, especially those already experiencing salinisation due to over-exploitation.

One of the major challenges facing water resource managers is coping with climate change uncertainties in the face of real-world decision making, particularly where expensive investment in infrastructure such as well-field design, construction and testing and laying of pipelines is required. As discussed by Dessai and Hulme (2007), this challenge presents a number of new questions, for example, how much climate change uncertainty should we adapt to? Are robust adaptation options socially, environmentally and economically acceptable and how do climate change uncertainties compare with other uncertainties such as changes in demand? Also, what relationships between supply and demand for groundwater exist in particular regions and how might global change affect these relationships and feedbacks? The answers to these questions leading to robust adaptation decisions will require the development of probability distributions of specified outcomes (Wilby and Harris, 2006) and negotiation between decision makers and stakeholders involved in the adaptation process (Dessai and Hulme, 2007). For lower income countries, availability of resources and building adaptive capacity are particularly important in order to meet water shortages and salinisation of freshwaters (IPCC, 2007).

According to the IPCC (2007), the array of potential adaptive responses available to human societies is very large, ranging from purely technological (for example, deepening of existing boreholes), through behavioural (altered groundwater use) to managerial (altered farm irrigation practices), to policy (groundwater abstraction licensing regulations). The IPCC (2007) argued that while most technologies and strategies are known and developed in some countries (for example, demand management through the conjunctive use of surface water and groundwater resources), the effectiveness of various options to fully reduce risks for vulnerable water-stressed areas is not yet known, particularly at higher levels of global warming and related impacts. Table 2 summarises supply-side and demand-side adaptation options designed to ensure supplies of water and groundwater during average and drought conditions. As explained by the IPCC (2008), supply-side options generally involve increases in storage

**Table 2** Types of adaptation options for surface water and groundwater supply and demand (based on IPCC, 2008)

| Supply side | Demand side |
|---|---|
| Increase storage capacity by building reservoirs and dams | Improve water-use efficiency by recycling water |
| Desalinate seawater<br>Expand rainwater storage | Reduce water demand for irrigation by changing the cropping calendar, crop mix, irrigation method and area planted |
| Remove invasive non-native vegetation from riparian areas | Promote traditional practices for sustainable water use |
| Prospect and extract groundwater | Expand use of water markets to reallocate water to highly valued uses |
| Develop new wells and deepen existing wells<br>Maintain well condition and performance | Expand use of economic incentives including metering and pricing to encourage water conservation |
| Develop aquifer storage and recovery systems | Introduce drip-feed irrigation technology |
| Develop conjunctive use of surface water and groundwater resources | License groundwater abstractions |
| Develop surface water storage reservoirs filled by wet season pumping from surface water and groundwater<br>Develop artificial recharge schemes using treated wastewater discharges<br>Develop riverbank filtration schemes with vertical and inclined bankside wells<br>Develop groundwater management plans that manipulate groundwater storage, e.g. resting coastal wells during times of low groundwater levels<br>Develop groundwater protection strategies to avoid loss of groundwater resources from surface contamination<br>Manage soils to avoid land degradation to maintain and enhance groundwater recharge | Meter and price groundwater abstractions |

capacity or water abstraction. Demand-side adaptation options rely on the combined actions of individuals (industry users, farmers (especially irrigators) and individual consumers) and may be less effective. Indeed some options, for example, those incurring increased pumping and treatment costs, may be inconsistent with climate change mitigation measures because they involve high energy consumption.

Examples of current adaptation to observed and anticipated climate change in the management of groundwater resources are few, with groundwater typically considered as part of an integrated water supply system. The ability of California's water supply system to adapt to long-term climate and demographic changes is examined by Tanaka et al. (2006) who concluded that the water supply system appears physically capable of adapting to significant changes in climate and population, albeit at significant cost. Such adaptations would entail large changes in the operation of California's large groundwater storage capacity, significant transfers of water among water users and some adoption of new technologies. In contrast to this example from North America, Ojo et al. (2003) discussed the downward trends in rainfall and groundwater levels and increases in water deficits and drought events affecting water resources availability in West Africa. In this region, the response strategies needed to adjust to climate change emphasise the need for water supply–demand adaptations. Moreover, the mechanisms needed to implement adaptation measures include building the capacity and manpower of water institutions in the region for hydro-climatological data collection and monitoring; the public participation and involvement of stakeholders; and the establishment of both national and regional co-operation.

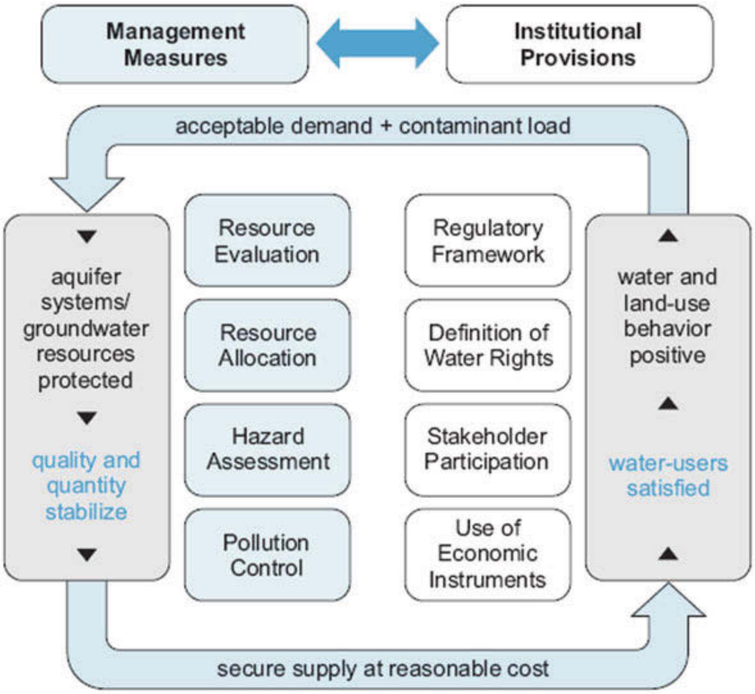
## Future Challenges for Groundwater Management

Three aquifer characteristics determine whether groundwater resources will ultimately prove sustainable: vulnerability to pollution under contaminant pressure from the land surface; susceptibility to irreversible degradation from excessive exploitation; and renewability of storage reserves under current and future climate regimes. These characteristics vary widely by aquifer type and hydrogeologic setting. Vulnerability to pollution is generally linked to the accessibility of an aquifer. Aquifers that are shallow and readily recharged are more likely to suffer pollution from agrichemicals and urbanisation (in particular, from low-cost wastewater disposal and careless disposal of industrial chemicals). Groundwater development and effluent disposal for urban water supply have far-reaching implications for public health, municipal planning and resource sustainability. In Europe land-use zoning is now used to protect vulnerable key aquifers that provide municipal water supply, as well as developing deeper, confined groundwater sources that are naturally protected from urban pollution (WWAP, 2009).

The tension between private and public services derived from aquifers remains. More convergent and sustainable resource use will be achieved only through substantial investment in management operations on the ground, working primarily through community consultation and cross-sectoral policy dialogue (WWAP, 2009). Such dialogue is supported by shared knowledge and common understanding of the current situation and future options. Good and reliable groundwater information is crucial to facilitate co-operation among stakeholders. All stakeholders should have easy access to reliable data on abstractions, water quality and groundwater levels. Adopting an adaptive management approach (Fig. 12) it should be possible to establish mutually acceptable regulations, adopted by all parties, based on a holistic definition of the aquifer system and understanding of the impacts of abstraction and contamination.

A significant challenge for the future development of groundwater sources is to raise political awareness of the issues involved. Unfortunately, increased scientific understanding of groundwater has not yet made a significant influence on resource policy making or featured prominently in global or national water policy dialogues, with discussion too often on groundwater development rather than groundwater management. Also, governance and practical management are not well funded and, as a consequence, opportunities for utilising groundwater resources sustainably and conjunctively are being lost and insufficient attention is being paid to the inter-relationship between groundwater and land-use planning (IAH, 2006). Often, decisions on groundwater development and management objectives, and the allocation of human, financial and environmental resources to meet these objectives, are made by leaders in government, the private sector and civil society, not by groundwater professionals alone. Therefore, hydrogeologists must help inform the

**Fig. 12** Integrated, adaptive management scheme for the protection of groundwater resources. After IAH (2006)



decisions of these leaders outside the water domain on such issues as spatial and development planning, demographic planning, health, education, agriculture, industry, energy, economic development and the environment (WWAP, 2009).

## Conclusions

Groundwater resources stored in aquifers can be managed given reasonable scientific knowledge, adequate monitoring and sustained political commitment and provision of institutional arrangements. Although there is no single approach to relieving pressures on groundwater resources given the intrinsic variability of both groundwater systems and socio-economic situations, incremental improvements in resource management and protection can be achieved now and in the future under climate change. Future sustainable development of groundwater will only be possible by approaching adaptation through the effective engagement of individuals and stakeholders at community, local government and national policy levels. The added uncertainty of global environmental and climate change may reinforce sound resource management, providing additional social and political impetus for science-based practice. In this way, the anticipation of change may have beneficial impacts on groundwater systems, even if the projected climate appears less favourable.

Finally, water resources management has a clear and rapidly developing association with many other policy areas such as energy, land use and nature conservation. In this context, groundwater is part of an emerging integrated water resources management approach that recognises society's views, reshapes planning processes, co-ordinates land and water resources management, recognises water quantity and quality linkages, manages surface water and groundwater resources conjunctively and protects and restores natural systems while considering climate change. This integrated approach presents new challenges for groundwater management. For example, better understanding is needed of the effects on groundwater recharge quantity and quality of large-scale plantations of commercial energy crops (IPCC 2008).

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